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BY

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ABSTRACT

Apparatus is described for obtaining shadow pictures of objects in rapid motion by properly timed spark illumination. The method is not new, but the means for carrying it out here described are believed more effective than any hitherto published.

The apparatus is so arranged that the illuminating spark occurs while the object to be photographed is between it and the photographic plate. There results an ordinary shadow of opaque objects, such as bullets, and inhomogeneities due to sound waves and turbulence of the air give distinctive patterns owing to refraction effects. In the illustrative photographs presented are to be found some striking sound-wave effects.

The photographs are presented primarily to illustrate the usefulness of the method, but they give interesting and important evidence concerning the gas leakage in a revolver, the acceleration of projectiles outside the muzzle and other phenomena attending the discharge of firearms. Other characteristics of the photographs are pointed out and in part explained.

CONTENTS

I. INTRODUCTION

Spark photography in which the illumination is provided by an electric spark of such short duration that a moving object appears stationary has many applications in the investigation of high-speed phenomena. The record obtained is not an image, no lens being used, but is simply the silhouette of objects between the light source and the photographic plate. Reference to previous work along similar lines will be made later in this paper.

Two distinct problems are presented in the photography of moving objects. One of these is the timing of the spark so that the desired epoch of the phenomenon under investigation may be photographed, and the other has to do with the duration of the spark. All of the photographs described in this paper were taken on plates not larger than 8 by 10 inches. A projectile moving at a speed of 2,700 ft./sec. would be in front of such a plate, and, therefore, in a position to be photographed for only 0.0003 second. If the projectile is to be photographed within an inch of a predetermined position, the time of occurrence of the spark must be correlated with the position of the projectile to within 0.00006 second.

The spark duration determines the amount of blurring, for if the projectile moves while the plate is being illuminated a streak will be recorded, the length of which depends on the duration of this spark. If the blurring is not to extend over more than one-sixteenth of an inch for a projectile moving at a speed of 2,700 ft./sec., the time of exposure must not exceed two-millionths of a second.

It is interesting to contrast the requirements which are imposed upon the apparatus just referred to with those imposed upon ordinary moving picture cameras in taking the so-called action photographs of the daily press. While many camera shutters are rated to operate in 0.0006 second, they seldom function in less than 0.002 second, and 0.005 second is a more common time of exposure. In photographing a racing car moving at 120 miles per hour, using a shutter which operates in 0.002 second, the car will move approximately 4.2 inches during the exposure interval. Exposure times which are satisfactory for photographs of polo matches, track and field work, etc., are 10 times too long for photographing a racing car and 10,000 times too long for photographing a projectile at right angles to its trajectory.

In order to secure a properly timed spark of suitable character there must be available a means of generating electrical energy at very high voltage, a means of storing such energy, apparatus for the regulation of the voltage and, finally, a means of releasing the stored energy at the proper time. The manner in which these parts are associated is shown diagrammatically in Figure 1. In our equip-

ment the generator consists of a motor-driven influence machine having two revolving plates 17 inches in diameter. A 0.024 μf Leyden jar condenser constitutes the means of storing the energy for the photographing spark. The apparatus for regulating the voltage of the condenser includes a dynamometer, or potential limiter, and a switch which disconnects the condenser from the influence machine when the voltage across its terminals reaches a definite value determined by the potential-limiter adjustment. The arrangement for releasing the photographing spark also consists of two parts. The first part is an electromagnetic switch which closes a trigger-spark gap. The second is an auxiliary device which serves

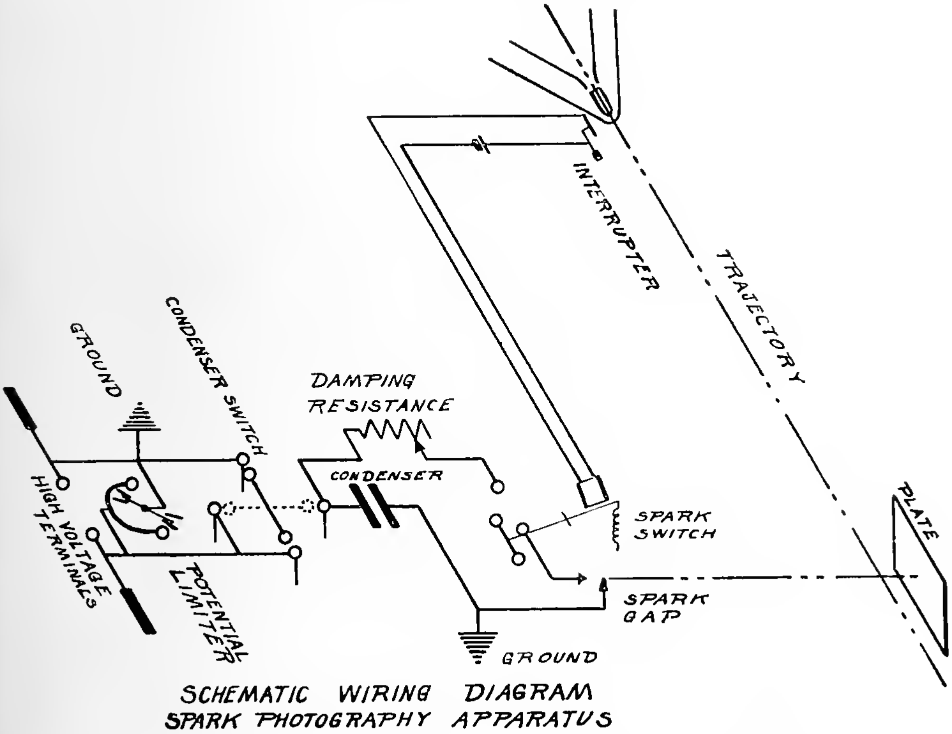

FIG. 1.—*Schematic wiring diagram of spark photography apparatus*

to time the operation of the previously-mentioned switch with respect to the phenomenon to be photographed. This auxiliary device takes different forms under varying circumstances; for example, when projectiles are being photographed well away from the gun an interrupter is used which is placed near the trajectory and which opens an electric circuit when the head wave of the bullet passes over it.

II. POTENTIAL LIMITER

The potential limiter, which is shown in Figure 2, starts the mechanism which disconnects the condenser from the charging circuit at a definite voltage. It consists of a pair of fixed spheres, *A*, a pair

of fixed vanes, *B*, and a pair of moving vanes, *C*, the centers of which are all at the same distance from the axis of rotation. The moving vanes are supported by a central spindle on which is also carried a cam which operates through a lever to close the make circuit, *D*, mounted on the supporting pillar. The two brass balls are connected by a rod which is insulated by a pyrex tube. The vanes are all conductively connected and may be rotated about the spindle as a center, thus giving a coarse adjustment of the potential at which the apparatus is set to function. The moving vanes are normally about 1 cm away from the fixed ones, and are restrained from swinging too far by

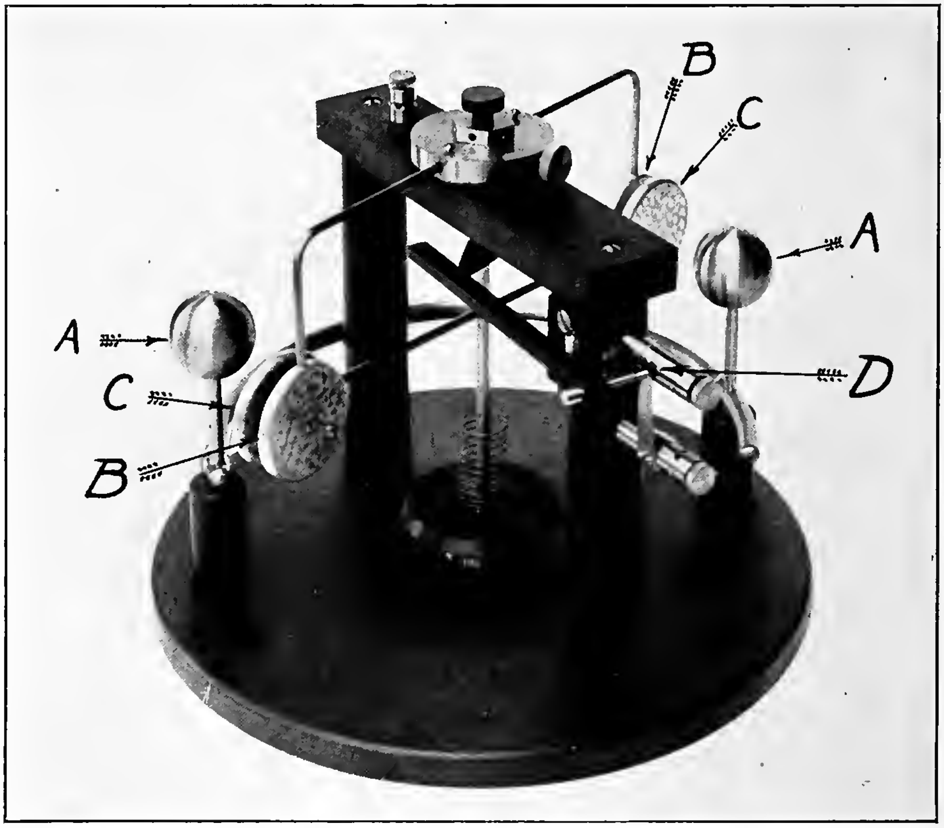

Fig. 2.—*Potential limiter*

a small stop attached to one of the stationary vanes (not visible in the plate).

When the potential across the terminals of the potential limiter is high enough, the repulsive force between the vanes and the attractive force between the spheres and the moving vanes operate to rotate the spindle. The rotating of this spindle closes the make circuit mounted on the supporting pillar by means of the cam and lever. The friction disk and spiral spring seen at the bottom of the vertical spindle serve to adjust the torque on the system, thus changing the potential at which the apparatus functions.

III. CONDENSER SWITCH

The condenser switch shown in Figure 3 performs three distinct functions. It disconnects the condenser from the influence machine, short circuits the latter, and closes a signal light circuit which indicates that the switch has operated. The movable arm, *A*, is cocked against a spiral spring, located under the upper plate of the apparatus, and held by the plunger, *B*, of an electromagnet which engages a catch on the arm. In this position the side of the influence machine which is not grounded is connected to the corresponding side of the condenser. When the potential limiter functions the solenoid is energized, thus retracting its plunger from the catch on the rotating

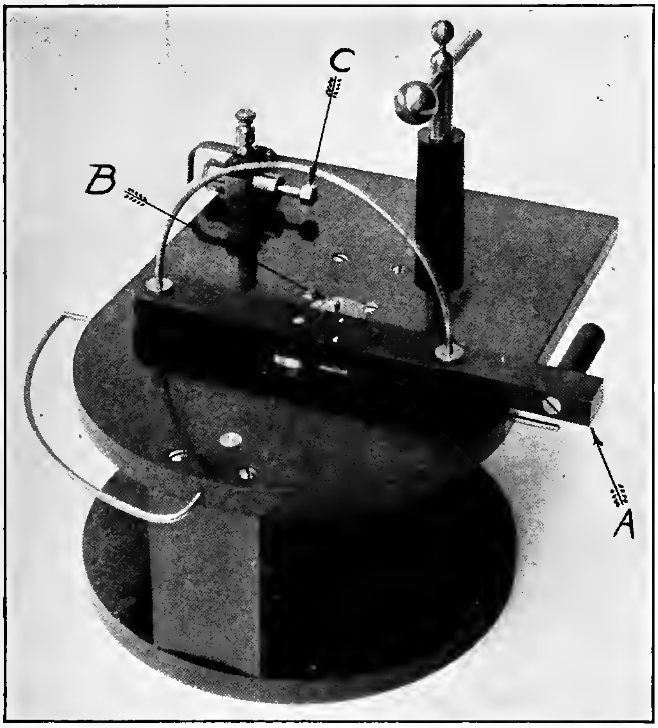

FIG. 3.—*Condenser switch*

arm. The arm under the action of the spiral spring promptly rotates through an angle of 90° to a position in which the condenser is disconnected and the terminals of the influence machine are short circuited. This is done to prevent the building up of potentials which would cause sparking and might easily fog the plate. The surges which such a discharge would induce in the spark circuit might easily cause a premature exposure or even a secondary spark, either of which would impair the results obtained.

One other feature of this switch is worthy of note. Since it functions when the apparatus is in readiness for the taking of a photo-

graph, some means is necessary to convey this information to the operator of the gun or to actuate a solenoid which will itself attend to the firing. At the back of the upper plate is seen a small buffer, *C*, for arresting the motion of the arm as it swings from the charging to the short-circuit position. This buffer also serves to make a circuit which may be used to light a signal lamp or to actuate an electromagnet which will fire the piece. This automatic feature of firing is of great value in certain types of work which will be discussed later.

IV. SPARK SWITCH

The switch by which the photographing spark is set off is shown in Figure 4. An aluminum arm, *A*, carrying at its end a small crossbar

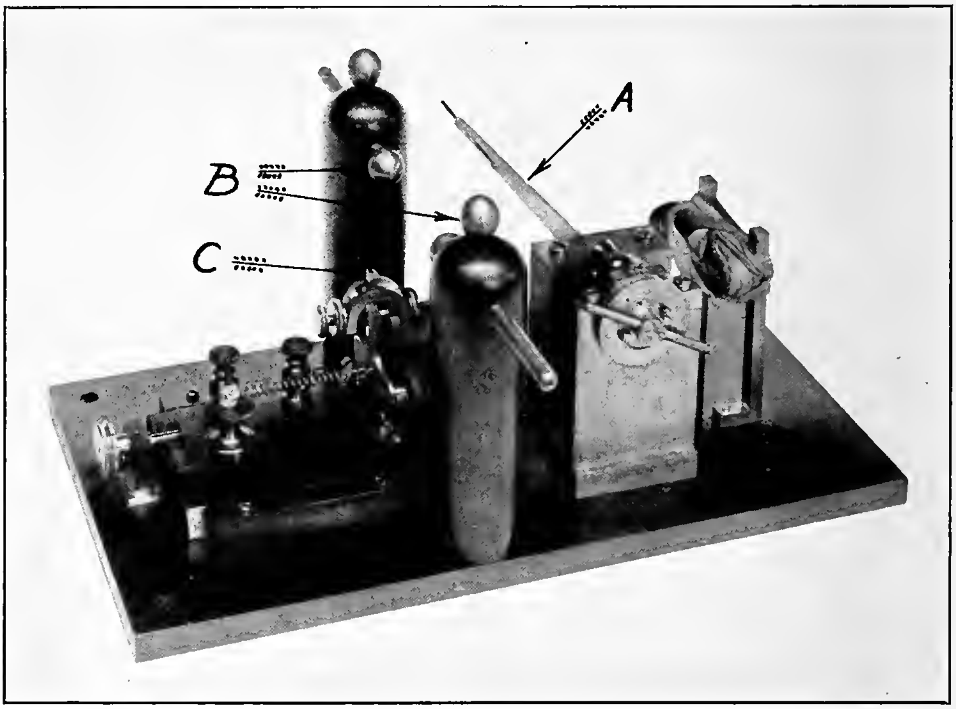

FIG. 4.—*Spark switch*

is cocked by means of a spiral steel spring, adjustable in tension. In the cocked position the arm is held below the two brass balls, *B*, of the spark gap by the catch, *C*, on the modified relay. Upon the release of the arm by the relay catch, the crossbar is carried through the gap between the two brass balls. In the system here described the change in length of the spark gap which is involved in triggering the spark is greater than in the other systems hitherto described. This makes possible the use of higher potentials and consequently a stronger photographing spark is assured. The tip of the switch arm and the relay catch are hardened, and adjustments are provided

for regulating precisely the amount of the switch-arm tip which the relay catch engages.

The interval between the breaking of the relay coil circuit and the actual release of the switch arm is approximately 0.0015 second. With the spiral spring adjusted to maximum tension the spark occurs 0.0033 second after the arm is released. The total lag for this adjustment is, therefore, 0.0048 second. The advantage of using the crossbar between two spheres to close the trigger gap over using one sphere only is that in the former case the gap is closed twice as fast for the same angular speed of the arm. Perhaps the most important feature of this switch is the wide adjustment in the time interval required to close the trigger gap which is secured by changing the tension on the spiral spring. At present the range extends from a minimum of 0.0048 second to 0.1 second or more. The minimum could, of course, be reduced still further by stiffening the actuating

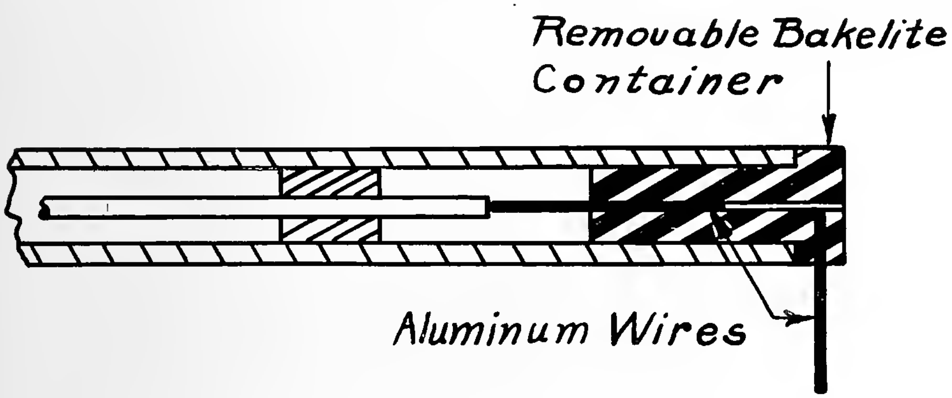

FIG. 5.—*Spark gap*

spring. It is well to keep in mind, however, that, in general, the total time interval elapsing between the break of the relay current and the occurrence of the photographing spark is not as important as the regularity of performance of the apparatus. The variation of the present switch seldom exceeds 0.00001 second and is usually very much less.

V. SPARK GAP

The gap in which the photographing spark occurs is shown in Figure 5, and consists of two aluminum wires 1 mm in diameter mounted in a bakelite cylinder in holes into which they fit tightly. This form of gap is very convenient because the gap may be removed from its holder and replaced by another with the same facility with which cartridges are changed in a revolver. This construction prevents wandering of the spark and keeps the source of light small and fixed in position.

VI. INTERRUPTER

The interrupter is of the type used in France in connection with the Joly chronograph (fig. 6). It consists of a metal box, *A*, about 2 inches in diameter, one side of which is closed by a metal diaphragm, *B*. An insulated contact arm, *C*, supported on a taut wire, *D*, normally rests against the diaphragm, closing a circuit. When the sound waves from a bullet or other source impinge upon the diaphragm, the impulse imparted to the arm causes it to swing away from the diaphragm, momentarily opening the circuit.

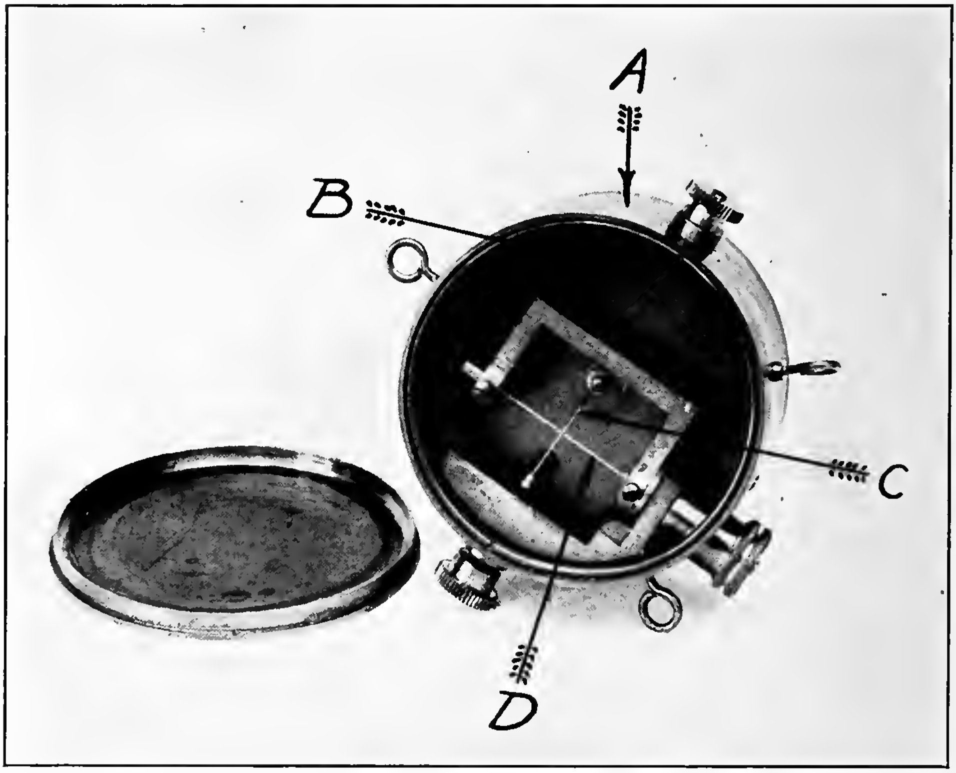

Fig. 6.—*Air-disturbance interrupter*

VII. CYCLE OF OPERATIONS

When a photograph of a projectile is to be taken the following steps are involved. The operator sets or cocks the spark switch and the condenser switch, having previously placed the interrupter a short distance away from the trajectory and at a sufficient distance from the photographic plate to allow for the 0.0048 second-time lag in the apparatus. This position may be determined by trial. An alternative procedure is to determine the lag of the spark switch experimentally and by a simple computation based on the value of the lag and the approximate speed of the projectile find the proper position for the head wave interrupter. The slide of the plate holder is drawn and after the influence machine has been started, the volt-

age across the condenser builds up until the point is reached at which the potential limiter functions. The closing of the contacts of the potential limiter energizes the tripping magnet of the condenser switch, which, in turn, promptly disengages the arm and short circuits the influence machine, thus preventing the accumulation of further charge on the condenser. This arm, through the buffer, automatically turns on the signal light and the operator immediately fires.

The bullet moves out from the muzzle and passes the interrupter in its progress toward the plate. As the sound waves which accompany the bullet pass the interrupter the circuit breaker is thrown open, the magnet of the relay is deenergized and the armature catch is released. The switch arm then closes the trigger gap and the condenser discharges through it and the photographing spark gap with which it is in series. If the interrupter has been properly located, the spark occurs at the instant the bullet arrives in the desired position in front of the plate.

VIII. GENERAL REMARKS ON THE APPARATUS

The entire apparatus with the exception of the interrupter is set up in a dark room, which the bullet enters through a cloth when firing in daylight and through an open door when firing at night. All of the regulating and control apparatus as well as the photographing spark gap are mounted in a dust-proof case. This case, which is about 14 inches wide, 24 inches high, and 4½ feet long, is divided horizontally through the middle. In the lower section thus formed the photographing spark gap is mounted, together with suitable diaphragms to prevent reflections from the sides of the box. The upper half of the case is divided into two compartments, in one of which the potential limiter and condenser switch are placed and in the other the spark switch.

All of these compartments are fitted with hinged doors, which make the entire mechanism readily accessible. Ruby lamps, with switches on the control board, serve the double purpose of furnishing safe light and drying the compartments.

Special attention has been paid to the insulation, the wires being incased in pyrex tubing. Corners, etc., of the high-voltage apparatus have been carefully rounded to reduce the density of charge, and consequently the leakage.

When the influence machine is difficult to start the secondary of a one-half kilowatt, 110 to 10,000 volt transformer, such as is used in spark radio transmitting, is temporarily connected across the terminals of the machine and the current in the primary is made and broken a few times by a suitable snap switch.

The motor which drives the influence machine is wired for remote control and can be stopped or started from either the control board on the apparatus or outside the apparatus room at the rifle rest.

IX. DAMPING OF THE SPARK CIRCUIT

As yet nothing has been said concerning the method by which the duration of the photographing spark is made sufficiently short. This adjustment is best made experimentally and is accomplished by taking a series of photographs, changing the resistance of the circuit by small increments for each photograph starting as near zero as possible. In this way the circuit is made to pass from the oscillatory state through the critically damped condition into the highly damped state. By this procedure the photographs obtained will first appear as multiple images of progressively diminishing intensity. As the resistance is increased the multiple images will eventually disappear, and a few of the photographs will have single images which appear reasonably sharp while beyond this the photographs, though single images, become more and more blurred as the resistance is progressively increased. An examination of these photographs will readily show which of the resistances used was best, and the range immediately adjacent to this point may then be investigated more in detail to determine the optimum value.

The rheostat by which the changes in the resistance of the spark circuit are made consists of resistance wire, wound with a suitable pitch, on a clean glass plate. It is probable that the duration of the photographing spark can not be made exactly the same for any two photographs because of the varying character of the resistance of the spark gaps themselves. Hence, we should expect some photographs to be slightly sharper than others, depending upon the nearness with which proper damping is approached.

X. ADVANTAGES OVER EARLIER APPARATUS

The present apparatus has many advantages over that previously described by the writer.[1] The present spark switch is operated by a spiral steel spring instead of rubber bands. This contributes greatly to the constancy of performance of the new switch, which also has a much wider range of adjustment, since it provides for any desired spark lag from 0.0048 to 0.1 second.

The insulation of the present system has been greatly improved over the former one and the design and workmanship of the apparatus are much better. The apparatus may be operated under weather conditions impossible with the former set-up, although the influence machine used is inferior to the one formerly employed. All the apparatus is inclosed in dust-proof, heated cases. Instead of being mounted in a tube 1 cm in diameter, the light gap of the present system is restricted to a small hole of 1 mm diameter so that the present gap is more nearly a point source than the former one.

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[1] Quayle, Journ. Frankl. Inst., 193, pp. 627–640; 1922.

XI. COMPARISON WITH OTHER METHODS

The first spark photographs of projectiles in flight seem to have been taken about 1881 by Prof. E. Mach, of the University of Prague, who carried out a remarkable series of experiments along this line. Professor Mach utilized the so-called Schlierenapparat devised by Toepler for making visible those portions of a transparent medium which differ but slightly in refractive index from that of their surroundings. Hence, his images were small and required the utmost in photographic manipulation to develop them. Professor Mach triggered his photographing spark by firing the bullet through a secondary trigger gap, and while this method is positive, the wires of the trigger gap appear in the photograph.

Dr. L. Mach in 1893 attacked the problem with several modifications of the earlier apparatus and a most ingenious trigger device. His efforts were attended by marked success. L. Mach's apparatus was also based upon Toepler's method, but he replaced the lens of the earlier apparatus by a large concave mirror which gave a larger field and more intense illumination. L. Mach triggered his spark by means of a compressional wave started by the passage of the projectile through a special device designed for the purpose.

From data found in Mach's papers and from general information concerning the rifles in use at the time his work was done it appears probable that the speed of the projectiles photographed by him did not exceed 1,900 ft./sec.

C. V. Boys (1)[2] in 1893 introduced the direct shadow method of bullet photography employed in this paper. The sound waves and other air disturbances produced by the flight of the bullet are recorded on the photographic plate owing to the fact that their refractive indices differ from that of the surrounding air. Boys used the triggering device employed by E. Mach, which shows in each picture, but his photographs are among the best ever obtained.

Excellent photographs similar to those of Boys's were published in Ordnance Pamphlet No. 422, United States Navy Department, 1913. The photographs were made by W. A. Hyde at the Bureau of Standards.

All of the methods of photographing projectiles in flight which have been discussed up to this time have one point in common, namely, that in triggering the photographing spark the motion of the projectile is interfered with in some way. In the earlier triggers the projectile closed a gap mechanically. Then L. Mach fired his bullets through paper cylinder heads causing a compressional wave in a small tube. The use of the interrupter described here and in the earlier publication (7) referred to yields photographs in which no

[2] See Bibliography, p. 276.

part of the photographing mechanism appears and in which the bullet is not touched in any way.

In making some of the photographs here presented the firing mechanism on the gun has been used to trip the photographic apparatus. In this case the lag in the mechanism takes care of the delay in the exposure necessary to permit the projectile to reach the desired position. Since the literature of the subject is extensive and sometimes difficult of access, the previous employment of a similar device may have escaped the writer's attention. But the method appears to be new and it will, therefore, be discussed briefly.

The essential feature of the timing trigger employed on the Springfield rifle is a small hinged inertia member which is momentarily left behind by the cocking piece as it moves forward toward the primer, thus opening an electrical circuit which trips the spark switch. At first glance such a firing mechanism trigger might seem to be preferable to the head wave interrupter previously referred to, but the effective use of such a mechanism is limited. If, for instance, a projectile moving at a speed of 2,700 ft./sec. is to be photographed 100 feet from the muzzle with this device a variation in the speed of the projectile of 100 ft./sec. would cause a variation of 4 feet in the position of the projectile when the spark occurs. With the interrupter functioning on the head wave at 15 feet from the plate the corresponding displacement due to the same variation in projectile speed would be only 0.6 foot.

The inertia trigger makes it possible to obtain photographs of projectiles over a range which may begin at the muzzle and extend out any reasonable distance without regard to the speed of the bullet relative to that of sound, the speed of the spark switch being changed to correspond with each different distance from the gun to the plate. The previous consideration of the effectiveness of the inertia trigger at distances remote from the muzzle must, of course, control its use. In the photography of projectiles at the muzzle of so-called hammerless guns, such a device, if designed to operate on the recoil of the arm, would function too late, because of the minimum of 0.0048 second, in which the spark switch will function.

In photographing projectiles moving at speeds greater than that of sound the interrupter has the advantage that once adjusted it is independent of the position of the gun as long as the speed of the projectile does not change appreciably. When the interrupter is employed to photograph projectiles moving at speeds less than that of sound the gun is so placed that the blast of the propelling charge actuates the circuit breaker, and in this case the gun must not be moved unless the speed of the spark switch is changed accordingly. On account of the minimum time lag of 0.0048 second in the apparatus there is a definite minimum distance below which the gun must

not approach the plate when the interrupter is being used, even though operating on the blast. This distance is about 13 feet for a projectile whose muzzle speed is 2,700 ft./sec.

We may say, therefore, that, in general, the inertia trigger is preferable in photographing phenomena at the muzzle and for very low-speed projectiles, but for high-speed projectiles at more than 13 feet from the muzzle the head wave interrupter is much more effective.

With revolvers, pistols, rifles, and shotguns having an exposed hammer a circuit breaker may be arranged to be tripped by the hammer in its fall toward the firing pin or primer as the case may be. Such a mechanism should be mounted to rotate about an axis coincident with that of the hammer so as to provide a coarse adjustment of the timing of the spark, the fine adjustment being made as usual by changing the tension of the spiral spring of the spark switch.

XII. APPLICATION OF SINGLE-SPARK PHOTOGRAPHY TO BALLISTICS

1. DETERMINATION OF PROJECTILE SPEED

It has been shown by C. V. Boys (1) that the slopes of the head and base waves of a projectile are dependent upon the ratio of the speed of the projectile to the speed of sound in the medium in which the waves are moving. It has been assumed that the speed of sound for the waves attending projectiles in flight had the normal value except in the immediate vicinity of the projectile itself. Photographs recently made and accompanied by simultaneous independent speed determinations indicate that this is not the case and that the situation is somewhat more complex than hitherto supposed. Speed measurements made on the assumption of Boys's simple theory and assuming the normal speed of sound may be in error by as much as 10 per cent. This subject is at present being investigated and the results are to be presented in a future paper.

2. ACCELERATION OF PROJECTILES AFTER LEAVING MUZZLE

There is, perhaps, no question in the realm of the ballistics of small arms upon which there has been so great a diversity of opinion as that of acceleration of a projectile after leaving the muzzle.

In 1897 Lieut. B. W. Dunn,[3] Ordnance Department, United States Army, said on this subject:

> Small-arm bullets should be considered as having their maximum velocities at points from 20 to 30 feet in advance of muzzle. They should gain in velocity over this distance, for the bullet is enveloped in gases moving in the same direction and with higher velocity. The velocity of the light gases is soon reduced by atmospheric resistance, and the bullet on passing out of the gaseous envelope

[3] Journal of the United States Artillery, 8, pp. 1–18; July, 1897.

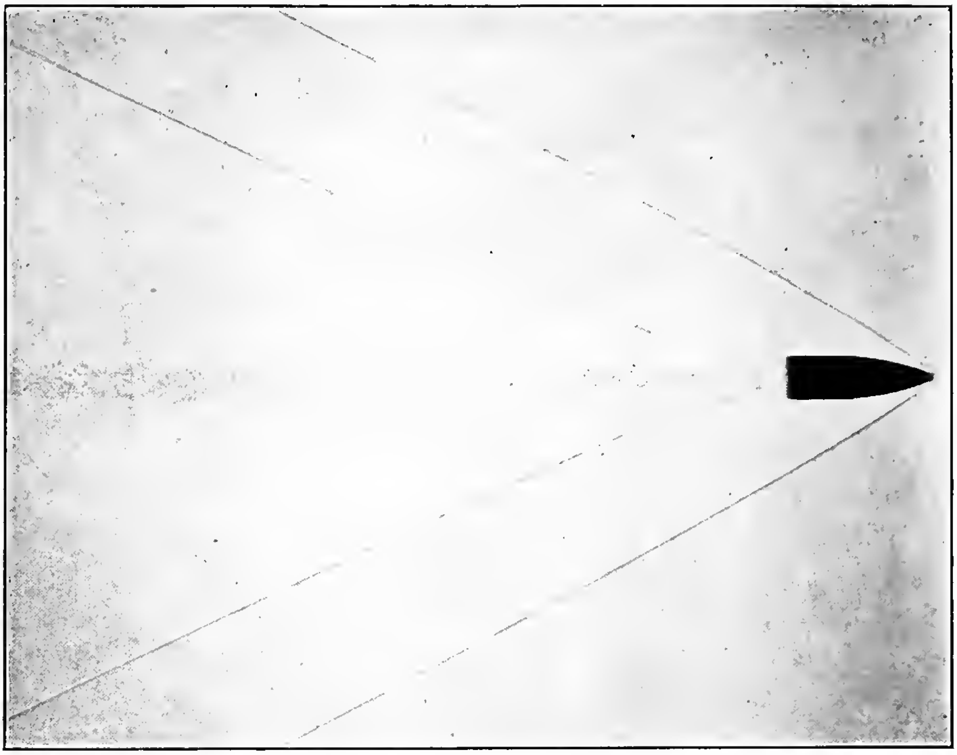

FIG. 7.—.30-caliber service bullet

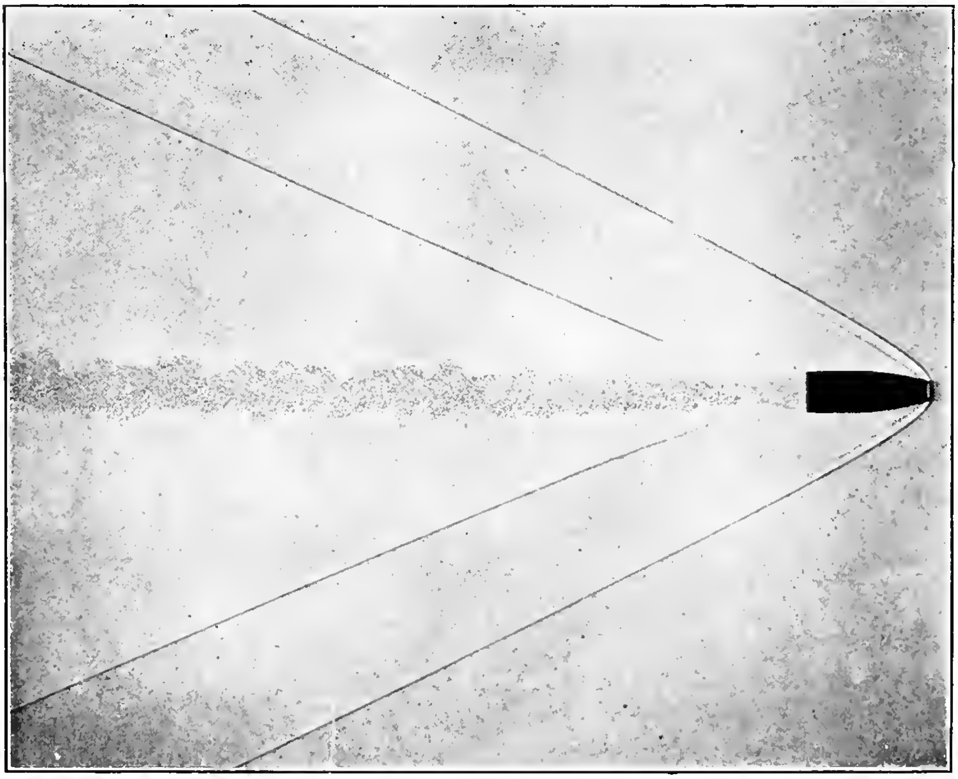

FIG. 8.—.30-caliber service bullet with modified head

encounters a volume of air of abnormal density. This volume of air, on account of the forward motion imparted to it by powder gases, does not at once retard the bullet in proportion to its density; but when firing takes place in a closed gallery with the last target near end of gallery, it is evident that the bullet must meet abnormal atmospheric resistance while moving over the last one or two target intervals.

FIG. 9.—*.30-caliber service bullet with modified head*

This opinion was quoted by John W. Hicks in his book on The Theory of the Rifle and Rifle Shooting as recently as 1919, and no refutation of the views expressed has been found in the literature. On the other hand, the photographs here presented of the region in front of the muzzle of a caliber .30 Springfield rifle show beyond any

reasonable doubt that the service projectile used ceases to be accelerated within a foot of the muzzle.

While the projectile is in the immediate vicinity of the muzzle it is subject to an accelerating force due to the outrushing gases of the propelling charge. In Figure 13 it will be seen that the projectile is clear of the muzzle and the propelling gases are blasting against the base. Since the gases are being deflected by the projectile it is, of course, being accelerated by them. Figure 14 shows the projectile

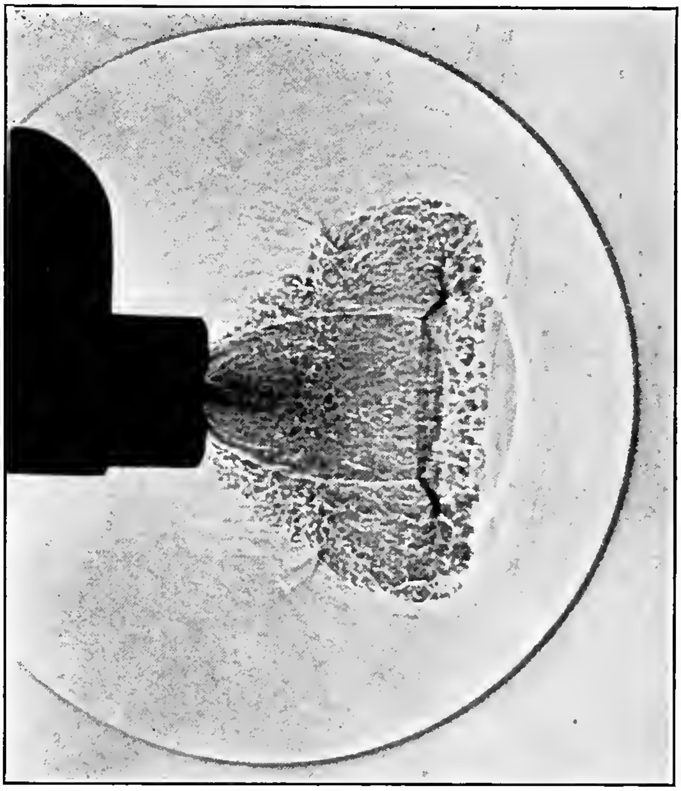

FIG. 10.—*Phenomena accompanying firing of .30-caliber Springfield rifle. Stage 1*

The cartridge has just been fired. The mushroom-shaped mass of gas in front of the muzzle probably consists mostly of air which is being pushed out of the barrel. The spherical sound wave seen just ahead of the gases was generated by a compressional wave from the barrel and originated with the unseating of the bullet from the cartridge case. The phenomena depicted in the following five photographs (figs. 11 to 15) show successive stages in the firing of the projectile, covering a total time interval of not over 0.0005 second.

approximately 1½ inches in front of the muzzle. It is overtaking the gases which have emerged in advance of it. Just behind the base is a compressional wave which is due to the fact that the gases are moving forward with respect to the projectile at a speed which exceeds that of sound in the gas medium involved. The actual speed of the gases at this moment is, therefore, somewhat greater than the sum of the speed of the projectile and the speed of sound in the medium.

The projectile is still being accelerated. Figure 15 shows the projectile 4 inches in front of the muzzle. The compressional wave at the base is still visible and indicates that the projectile is not yet clear of the accelerating effect of the outrushing gases.

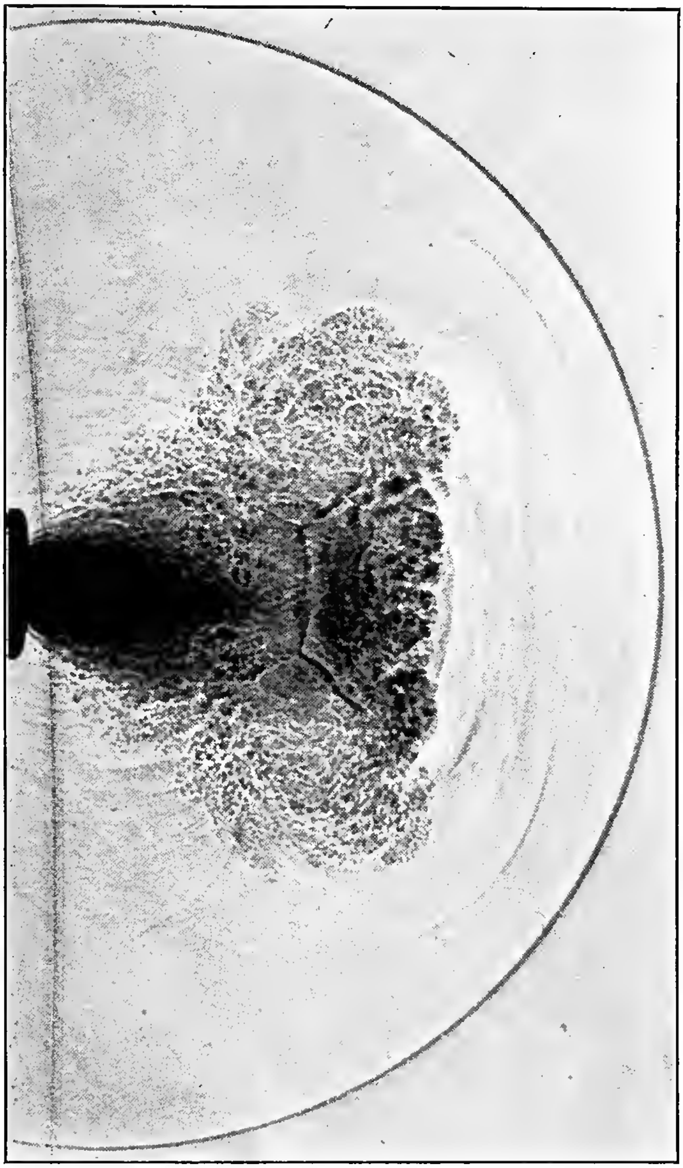

FIG. 11.—*Phenomena accompanying firing of .30-caliber Springfield rifle. Stage 2*

The mass of gas in front of the muzzle consists of air which has been pushed out of the barrel together with leakage gases. The sound wave is ahead of all other disturbances.

Figure 16 does not show the muzzle, but measurements made at the time the photograph was taken show that the center of the plate was 11 inches in advance of the muzzle. This photograph shows that the projectile has outdistanced all other effects of the discharge

and that it will (with the possible exception of a few stray powder particles) never be overtaken by any blast effects. The projectile is already moving through the normal atmosphere and is, therefore, subject to the retarding forces considered in exterior ballistics. At this stage and later there is no compressional disturbance in advance of the sound wave M except that which is due to the projectile itself.

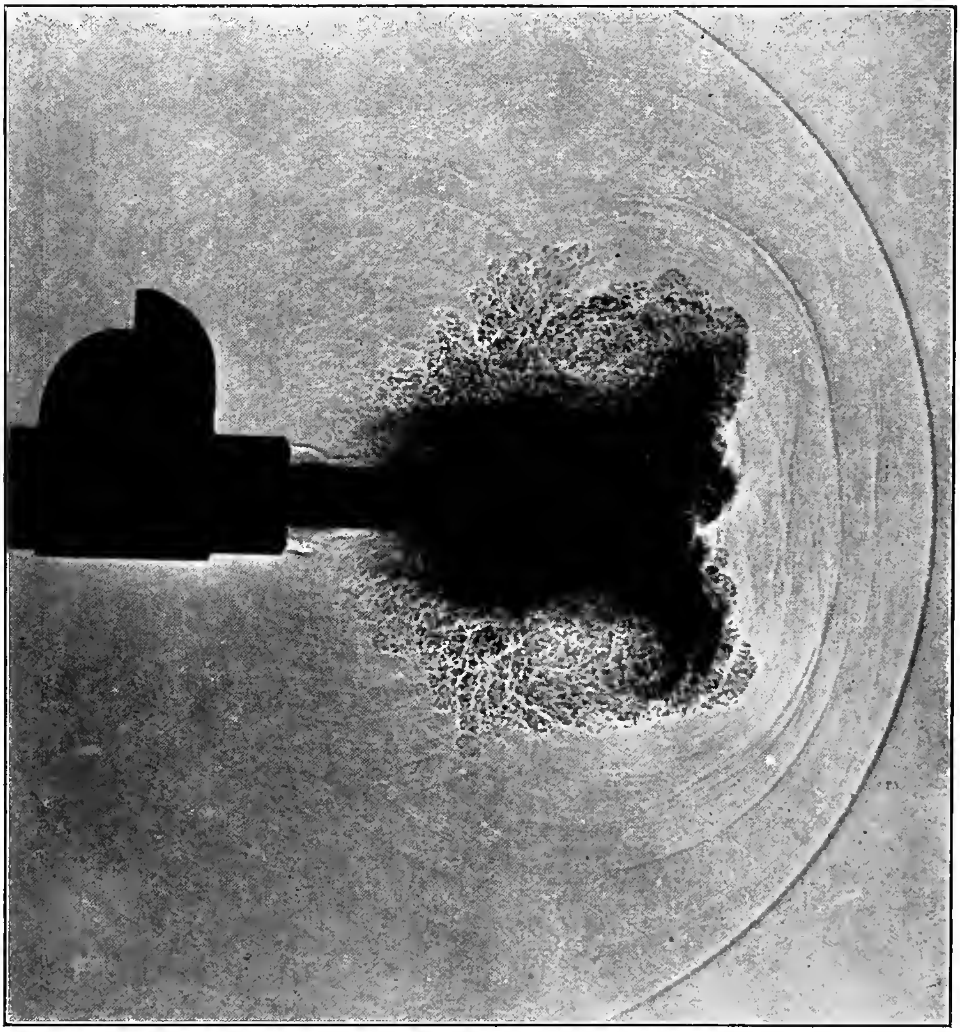

Fig. 12.—*Phenomena accompanying firing of .30-caliber Springfield rifle. Stage 3*

The projectile is now almost completely out and the escape of the propelling gases at the base is just beginning.

The powder particles which have head and base waves and turbulent wakes similar in all respects to those of the projectile form an irrelevant exception to the above statement.

It is well to keep in mind that in order to accelerate the projectile the gases themselves must move at speeds higher than that of the projectile. In the case of the service rifle this is approximately

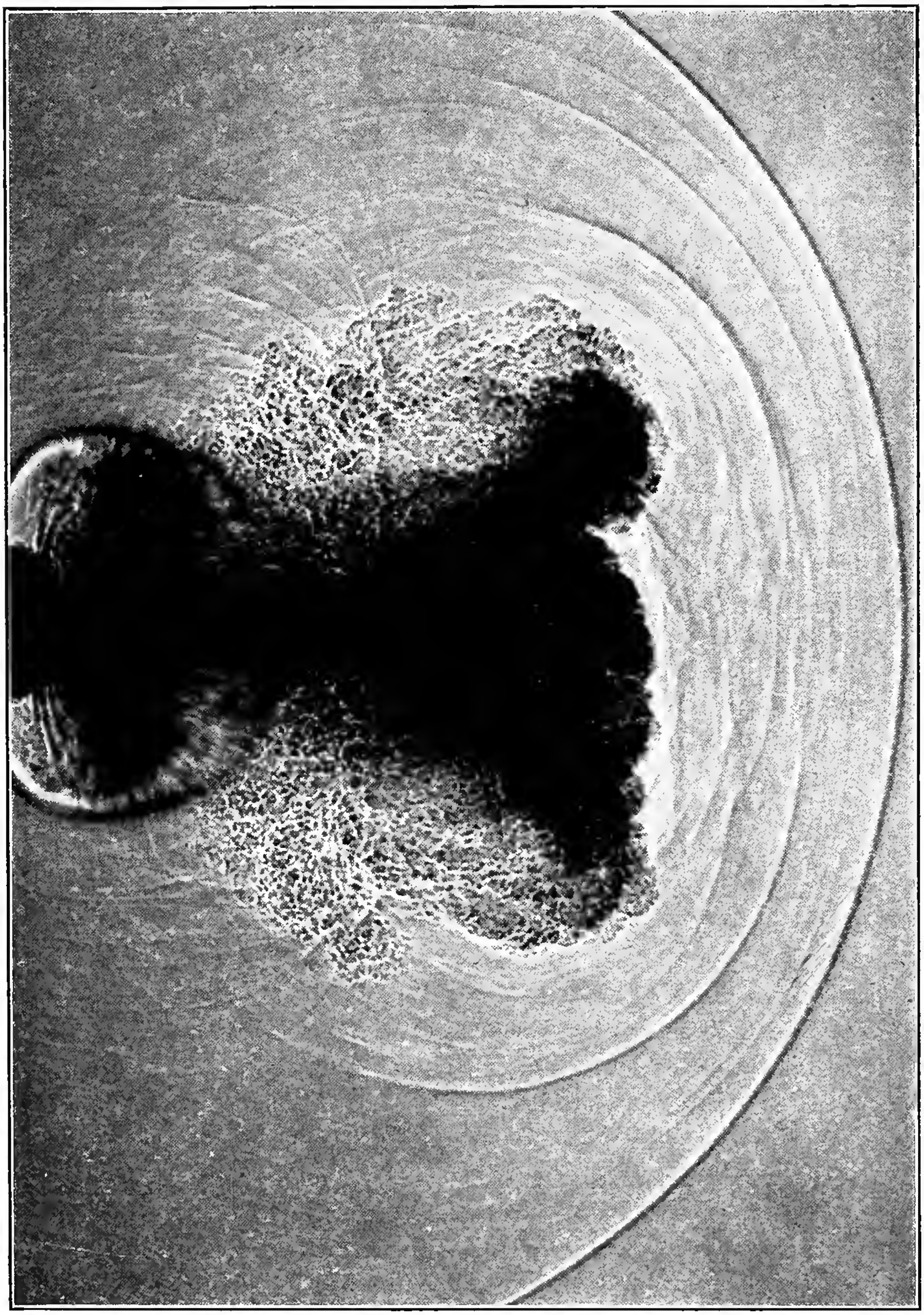

FIG. 13.—*Phenomena accompanying firing of .30-caliber Springfield rifle. Stage 4*

The projectile is now clear of the barrel and since the propelling gases are being deflected by it, is still being accelerated.

2,700 ft./sec. However, gases of the propelling charge moving at a speed slightly less than 2,700 ft./sec., although unable to accelerate the projectile are still capable of producing considerable disturbance as is evident by the swirling sand, etc., when firing over a parapet.

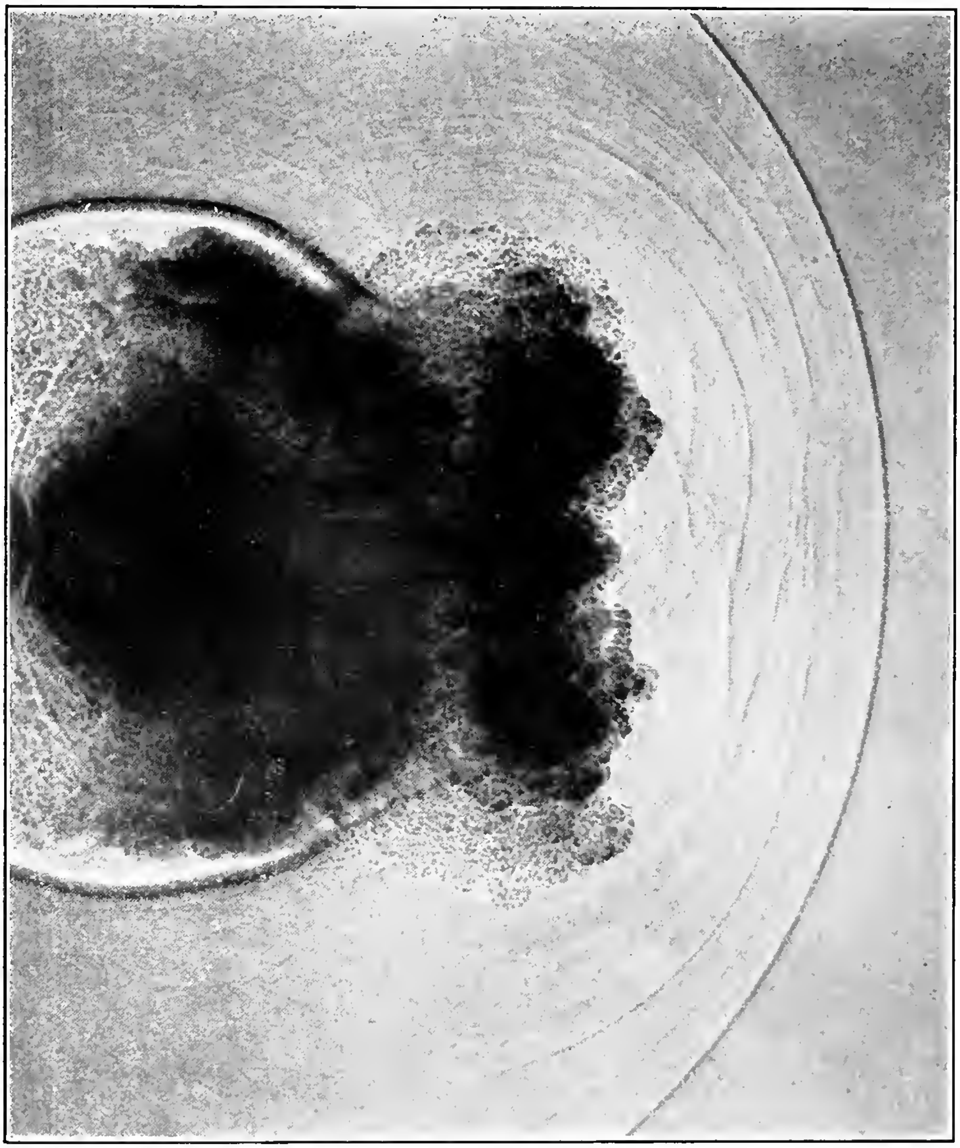

FIG. 14.—*Phenomena accompanying firing of .30-caliber Springfield rifle. Stage 5*

The projectile is approximately 1½ inches in front of the muzzle. It is overtaking the gases which emerged from the muzzle in advance of it. The original photograph shows just behind the base a compressional wave due to the gases which are moving forward with respect to the projectile at a speed exceeding that of sound in the gas medium involved. The projectile is still being accelerated.

It is, therefore, not surprising that the blast should have been supposed to have a far greater effect than it really has.

Figures 22, 23, and 24 furnish information regarding the acceleration of a .45-caliber revolver bullet after emerging from the muzzle. In Figure 22 the bullet has just cleared the muzzle, its base being

about one-eighth inch out. In this case, as in the rifle photographs previously mentioned, the gases are being deflected by the bullet and, hence, it is still being accelerated. In Figure 23 the bullet is about 1.75 inches out and since the gases are being deflected by the bullet it is still being accelerated. In Figure 24 there is no indication that the gases which surround the bullet are moving faster than the bullet itself. It seems, therefore, that with this particular revolver

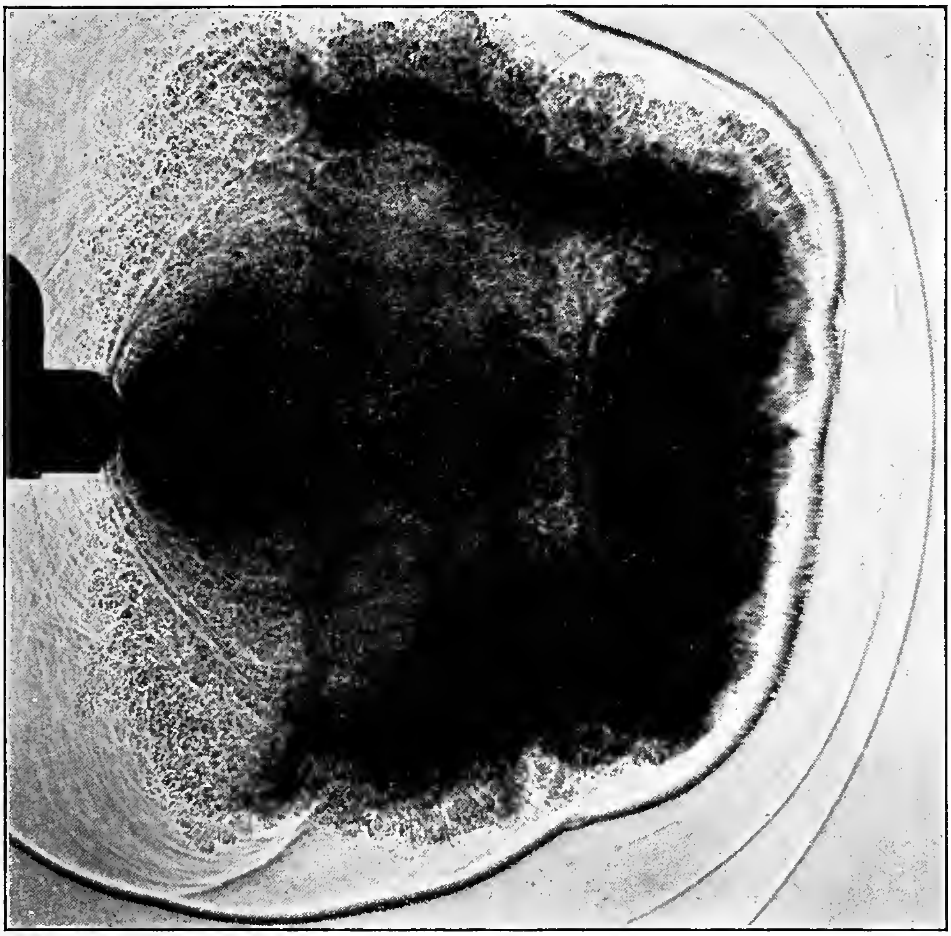

FIG. 15.—*Phenomena accompanying firing of .30-caliber Springfield rifle. Stage 6*

The projectile is approximately 4 inches in front of the muzzle. The compressional wave at the base is still visible and indicates that the projectile is still being accelerated.

and cartridge, the acceleration of the bullet by the gases of the propelling charge did not extend out more than 6 inches in front of the muzzle.

3. GAS LEAKAGE

The effectiveness with which a projectile seals the gases which drive it through the barrel is an important consideration in interior ballistics. Figure 10 shows the muzzle of a .30-caliber Springfield rifle with a mushroom shaped mass of gas just in front of it (probably

consisting mostly of air) which is being pushed out of the barrel by the advancing projectile. Figure 11 represents a slightly later stage in which the leakage gases have become quite dense. Figure 12, taken just an instant before the complete emergence of the projectile, shows quite a cloud of the leakage gases just ahead of the projectile.

Figures 17 and 18 show the muzzle of a .45-caliber revolver just after the cartridge has been fired. The unseating of the projectile

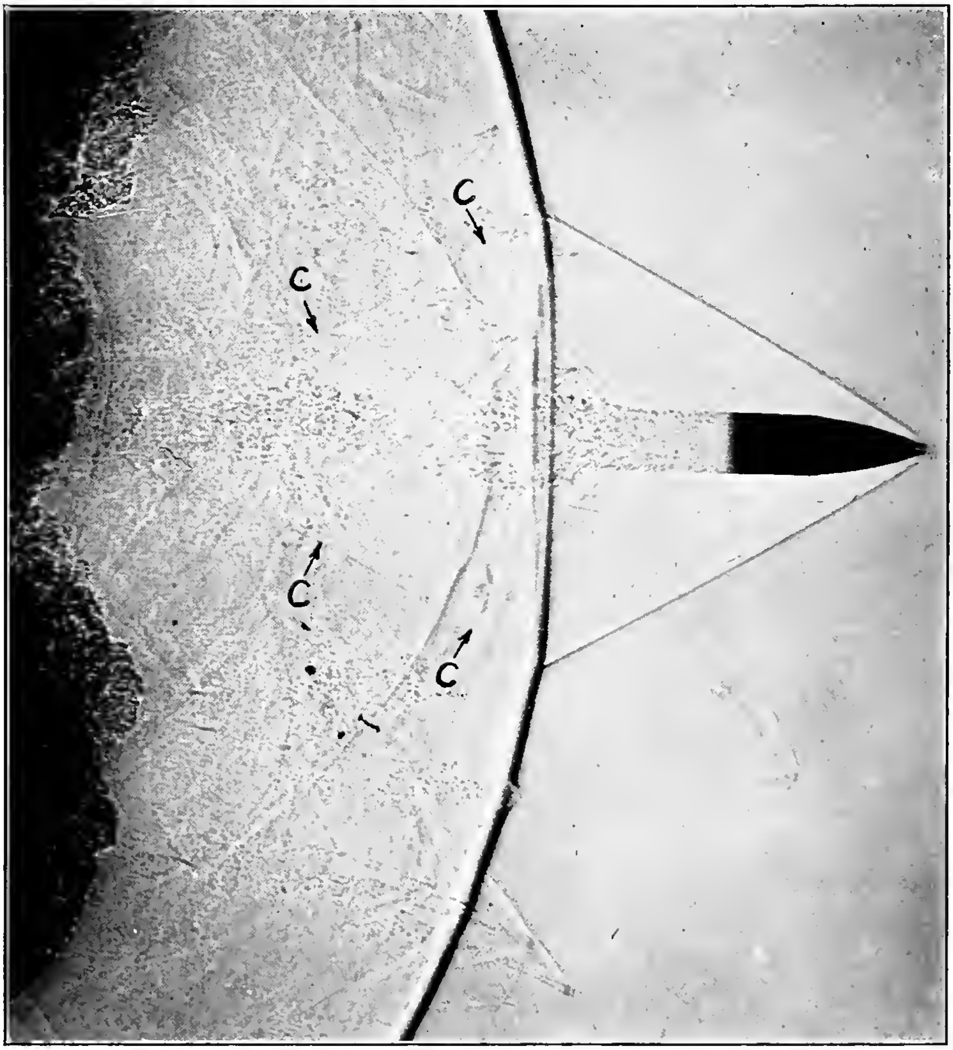

FIG. 16.—*Phenomena accompanying firing of .30-caliber Springfield rifle. Stage 7*

The muzzle is not shown, but measurements made at the time the photograph was taken show that the center of the plate was 11 inches in advance of the muzzle. Here the projectile has evidently outdistanced all other effects of the discharge and will (with the possible exception of a few stray powder particles) never be overtaken by any of them. The projectile is already moving through the normal atmosphere and is therefore already subject to the retarding force considered in exterior ballistics.

from the cartridge case has pushed some air out of the barrel behind the sound wave. Figures 19, 20, and 21 show the same phenomena at successively later stages. In Figure 21 the projectile is nearly out of the muzzle.

The 250-grain lead bullet 0.458 inch in diameter originally designed for use in the .45-caliber Colt's double-action revolver, model 1909, was not available when these photographs were taken. The cartridges actually used were those regularly issued for use in the .45-caliber Colt's automatic pistol, model 1911. The bullet of this type of cartridge is a 230-grain cupro-nickel jacket ball and has a diameter of 0.450 inch. When used in the revolver it is to be expected that, other things being equal, the smaller bullet would give the greater leakage.

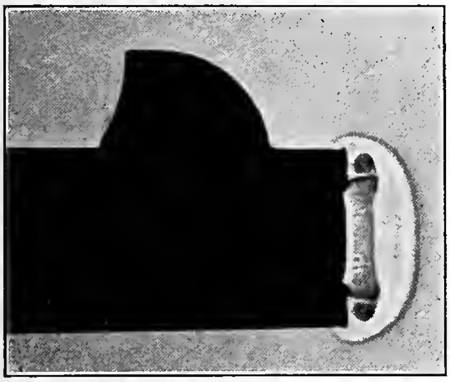

Fig. 17.—*Phenomena accompanying firing of .45-caliber revolver. Stage 1*

The figure shows a compression wave just emerging from the muzzle. A vortex ring may be seen close against the muzzle. Later stages of the phenomena are shown in Figures 18 to 24, covering a total time interval of about 0.002 second.

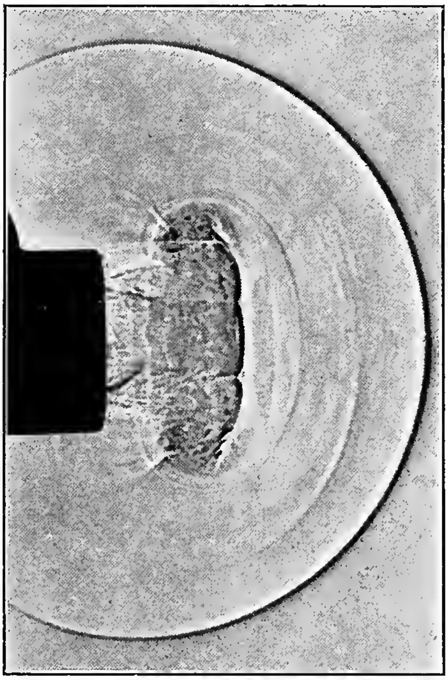

Fig. 18.—*No evidence yet of gas leakage. Stage 2*

4. SOUND-WAVE PHENOMENA AND GAS MOTION AT THE MUZZLE OF SMALL ARMS

Figures 27 and 16 show that the head wave of the projectile does not extend into the region behind the wave M and other photographs not here reproduced in which the projectile is just penetrating the wave M show the same phenomenon. From this it follows that the speed of the projectile relative to the gas, in this region, is less than the speed of sound in the gas, for otherwise a head and base wave would be formed. It, therefore, follows that the gases behind this wave are moving forward at considerable speed or that the speed of sound in this medium is quite high or that a combination of these conditions exists.

If the absence of the head wave, above mentioned, is due to the forward motion of the gases inside the wave M a stationary projectile set up in this region should show a head wave pointing in the direction from which the gases are coming, providing that their speed is above that of sound in the medium. However, the actual experi-

ment, the result of which is shown in Figure 27 showed no such wave at the nose of the stationary projectile and therefore G, the speed of the gases is less than S_G, the speed of sound in them. However, when this fixed projectile pierced the wave M it started an ordinary sound wave S, which at the moment it was photographed

FIG. 19.—*Note the ring-shaped advance guard of air and the leakage gases which now appear positively for the first time, the well-developed sound wave and the small particles of powder residue, each of which has its wake and waves, the slope of the latter being indicative of their speed. These particles were left in the barrel by a previous discharge. Some of them are going so fast that they have advanced beyond the sound wave. Stage 3*

had attained a diameter (as measured on the plate) of 1.44 inches. We may assume that the center of this wave was originally at the point of the bullet, but a pair of compasses will show that its center is now displaced about 0.38 inch, and that it is practically undistorted. This absence of distortion of the spherical wave while its

center has been moved 0.38 inch indicates reasonably uniform motion of the medium in which it is propagated. Furthermore, if the gases inside the wave M were moving forward with the speed of sound in the medium then the portion of the spherical sound wave nearest the muzzle could not move from the point of the projectile at which it started. If, on the other hand, the gases were stationary the wave would expand keeping the point of the projectile as a

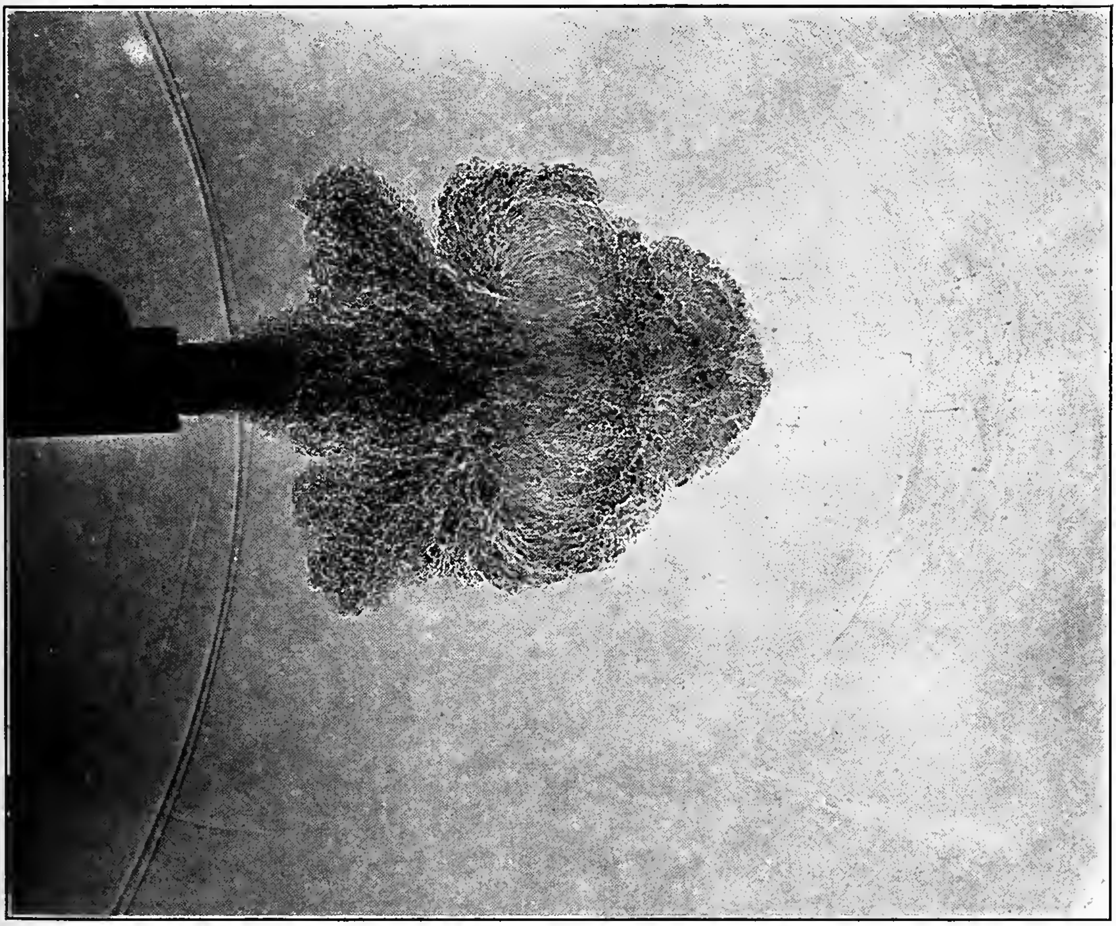

FIG. 20.—*The muzzle wave is now leaving the plate, the gases are pushed far out with most of the powder particles well ahead. Stage 4*

Note that for the first time the wave which has its origin at the junction of the cylinder with the barrel is now moving on to the plate. It is seen about one-half inch ahead of the muzzle.

center. The actual case is somewhere between these two. While the sound wave has moved out until its radius is approximately 0.72 inch, it has been moved forward as a whole 0.38 inch; hence the forward speed of the gases must be 0.38/0.72, or 0.53 that of the speed of sound in the gases.

The approximate ratio of the speed of sound inside the wave M to that of the wave itself may be obtained by considering the evi-

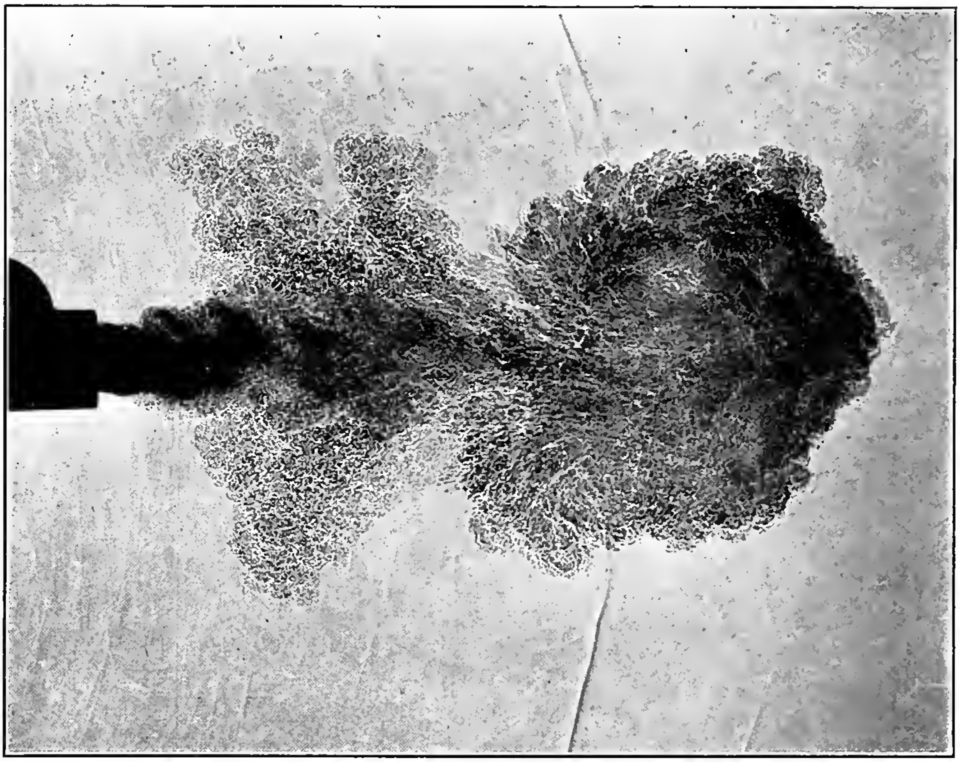

FIG. 21.—*The leakage of gases past the bullet is now nearly over. The sound wave from the muzzle has passed off the plate and the wave from the cylinder has moved more than half way across. The bullet is nearly out of the barrel. Stage 5*

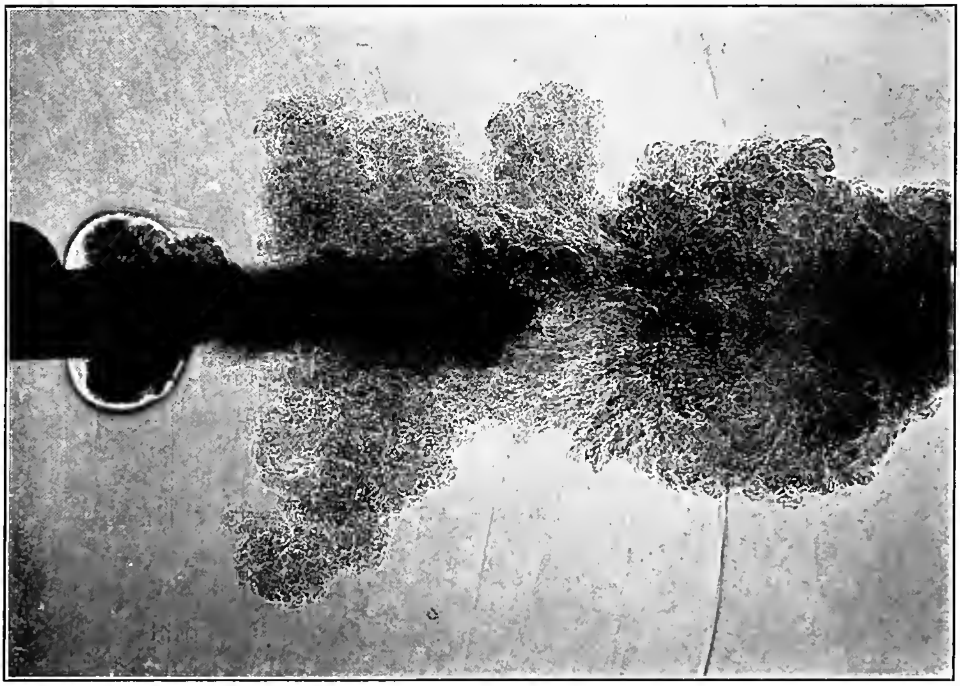

FIG. 22.—*The base of the bullet is now one-eighth of an inch outside of the muzzle and the sudden release of the pent-up gases behind it has started a new sound wave. The shape of this wave is that of an oblate spheroid, since its source is not a point, but a circle whose diameter is equal to that of the bullet. The wave from the cylinder is now well across the plate. Stage 6*

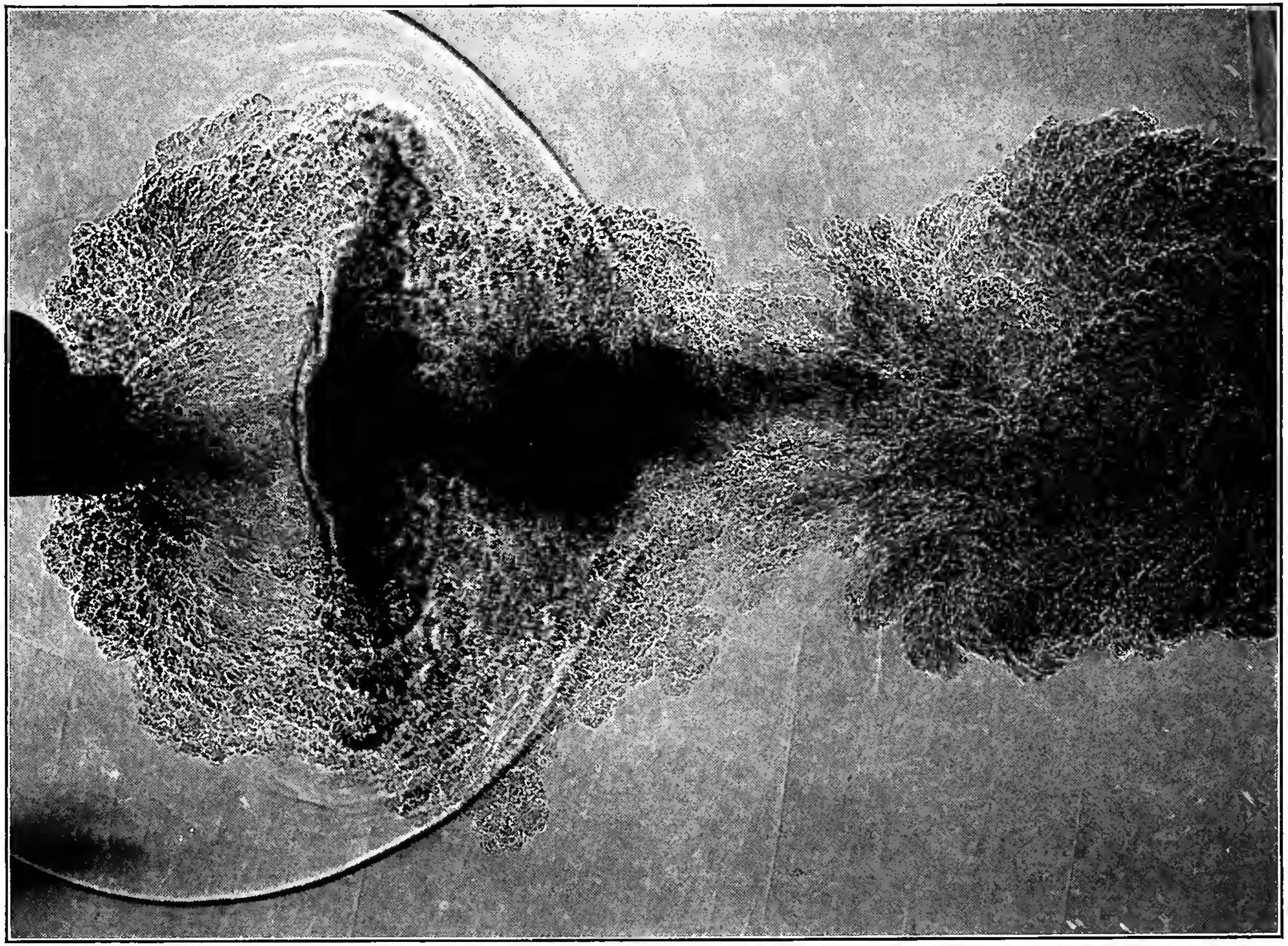

FIG. 23.—*The second muzzle wave has now developed into much greater proportions. The bullet is well out of the muzzle and is still being accelerated. The outrushing gases are impinging on its base and being deflected. Some of the gases which are going faster than the bullet have blown through the spherical wave in the center of the plate. Stage 7*

dence regarding their relative motion. Figure 27 shows that during the time required for the wave *M* to move from the point of the fixed projectile out to its present position, a distance of about 0.75 inch, the small spherical wave generated by the impact of *M* on the fixed projectile has developed a radius of 0.72 inch. Hence, it would appear that the speed of sound inside the wave *M* is about equal to that of the wave *M* itself at the instant represented in this figure.

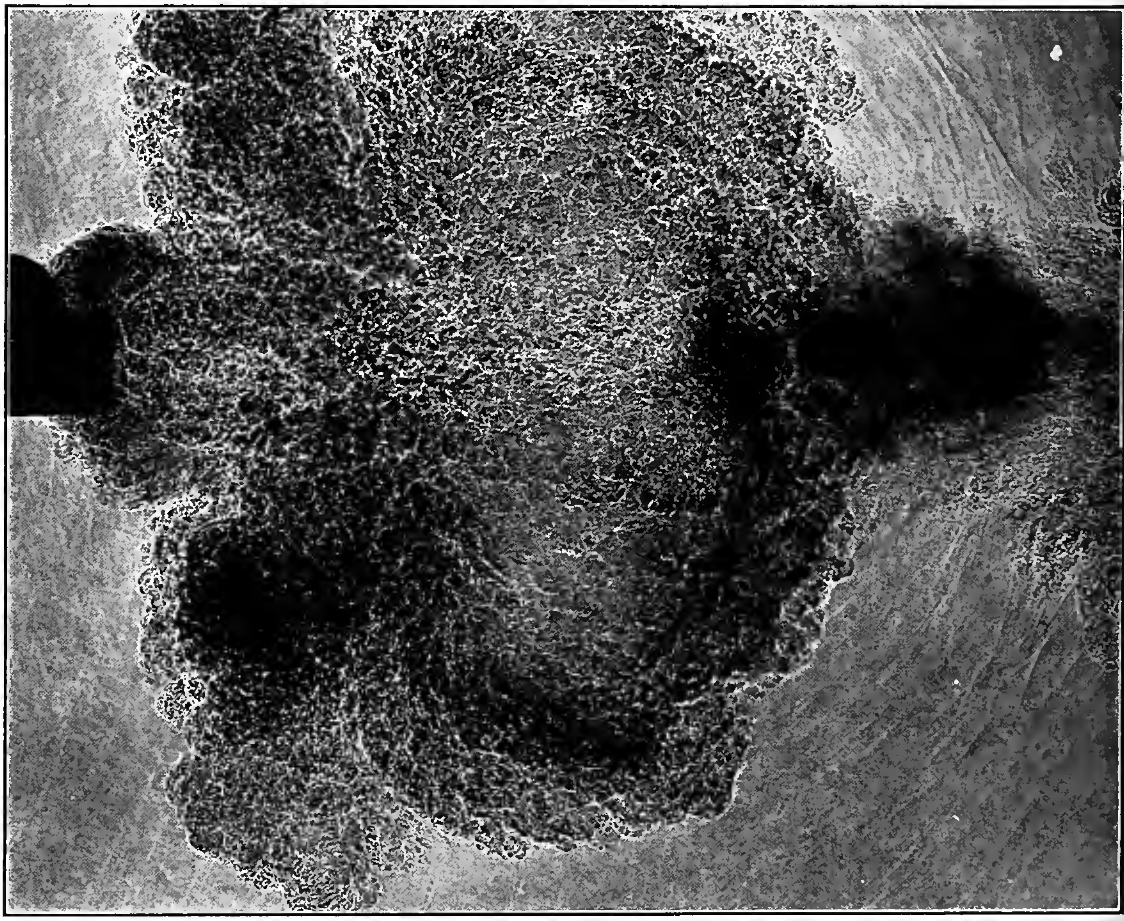

FIG. 24.—*Here the gases are no longer being deflected by the bullet, hence it is no longer being accelerated. The fuzzy appearance of the bullet is due to the refraction of the light as it passes the bullet and is caused by the gases which surround it. Stage 8*

We had previously concluded that the speed of the gases themselves at the instant represented by the photograph was approximately half the speed of sound in the medium.

From the relative positions of the moving projectile and wave *M* it follows that the average speed of the projectile is slightly greater than that of the wave *M*, assuming that the base of the projectile and the wave left the muzzle at very nearly the same time. If we also assume that the speed of the wave *M* has not increased, then

since we know that the speed of the bullet has increased somewhat above its mean speed, it follows that the present speed P of the bullet is greater than the present speed W of the wave. Hence, the speed of the gases is something less than half as large as that of the projectile, and the speed of sound in these gases is something comparable with that of the projectile.

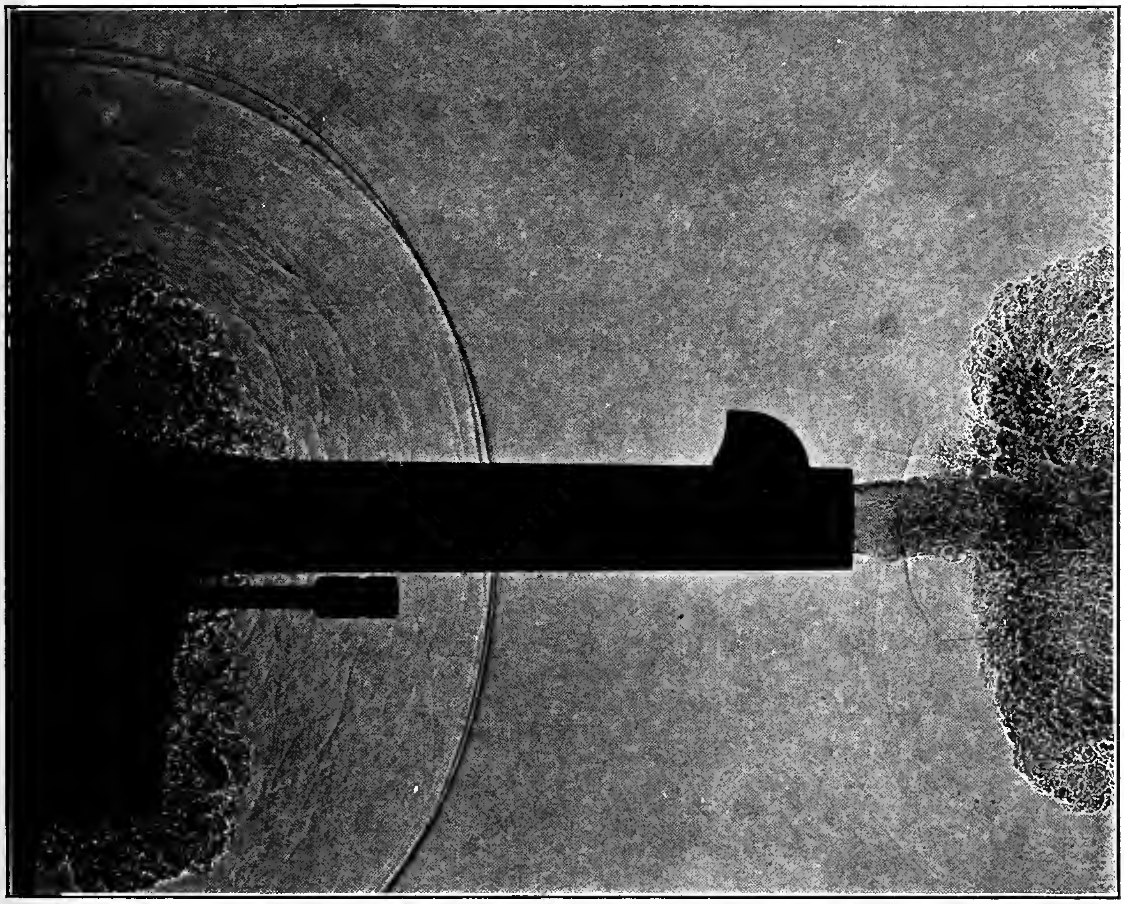

FIG. 25.—*Sound wave generated at cylinder of .45-caliber revolver. Stage 1*

The sound wave which starts from the junction of the cylinder with the barrel is clearly shown. The presence of this wave clearly demonstrates the futility of attempting to silence a revolver by attaching various contraptions to the muzzle. The bullet is still in the barrel, and the gases of the propelling charge which are leaking past the bullet are still close to the muzzle.

If in Figure 28 we let—

P = speed of projectile,

W = speed of the wave M,

G = speed of gases immediately behind M,

S_A = speed of sound in free air,

S_G = speed of sound in gases immediately behind M.

The arguments just presented may be summarized as follows:

$$G = \frac{1}{2} S_G \tag{1}$$

$$S_G = W \tag{2}$$

$$P > W \tag{3}$$

The condition that no head wave shall exist behind the wave M is—

$$P - G < S_G \tag{4}$$

or in view of (1) and (2)

$$P < 3/2\, W \tag{5}$$

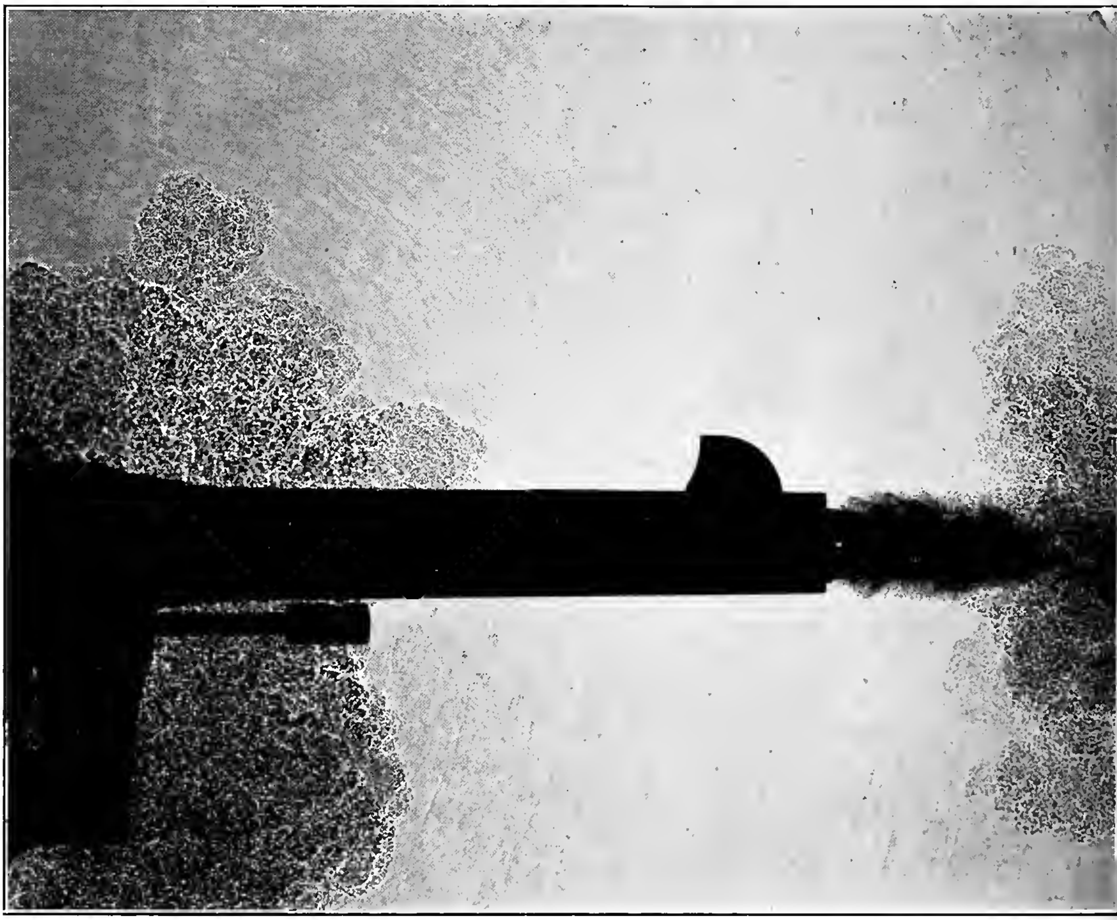

FIG. 26.—*This plate shows the bullet with only one-eighth of an inch of its base still in the barrel. The leakage rate is now much greater*

But it was found from the relative positions of the wave front M and the projectile that P is only slightly greater than W, which is broadly represented by equation (3). It, therefore, follows that condition (5) is satisfied, and the absence of the head wave in the region behind M is accounted for.

Where the head and base waves of the projectile begin on the wave M, the intersections of the waves represent singular points in the medium where the pressures and densities undergo more or less

abrupt changes. It is to be expected that such points will become the origin of a wave disturbance. As the intersections of the head and base waves with the wave *M* expand into larger circles with the progress of the projectile these points of wave origin change their position on the wave *M*. By plotting according to Huyghens, the waves resulting from such moving line sources the existence of the wave front *CC* is satisfactorily accounted for. Figure 29 shows the construction of such a wave. In constructing this figure it has

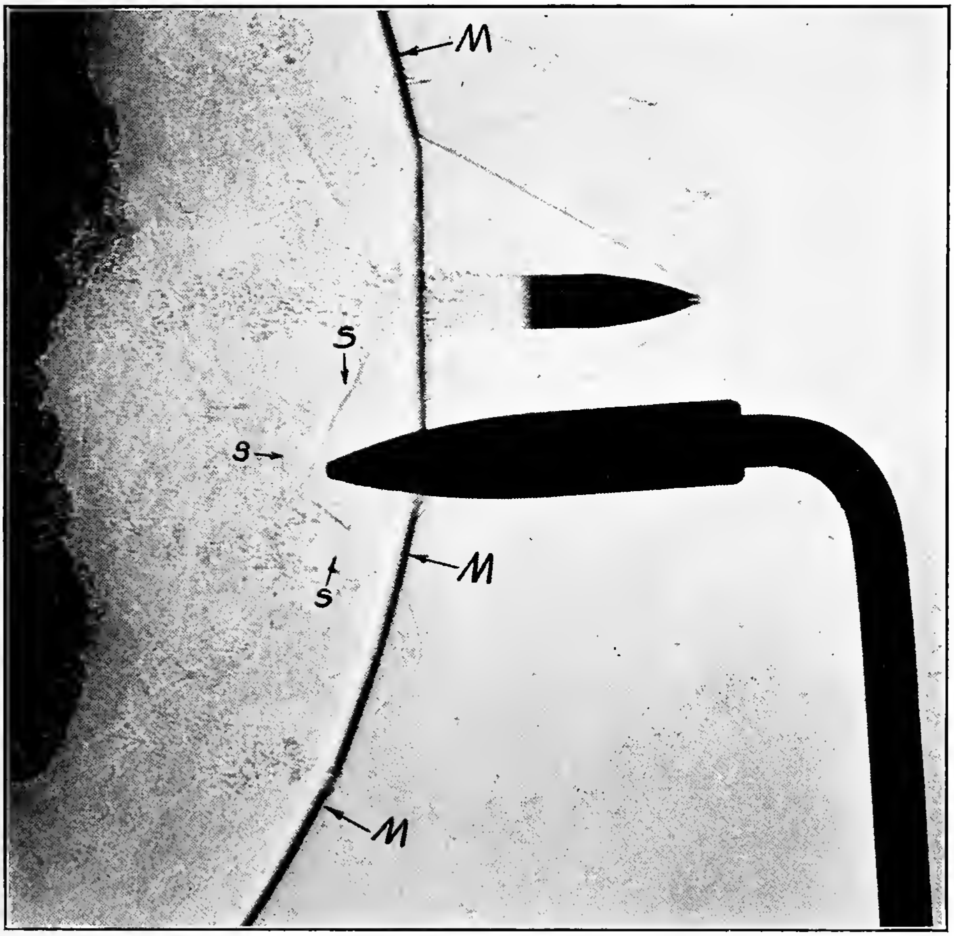

FIG. 27.—*Bullet passing near stationary object*
Photograph made to establish nature and state of motion of gas immediately behind the wave *M*.

been assumed that the speed of *P* along the wave *M* is uniform. This is justifiable to a first approximation. It is true that the medium behind *M* is moving at a speed which is, as we have seen, approximately half that of the projectile. The speed of sound in this medium is only a little below that of the projectile. These conditions, however, do not greatly modify the construction which at best can only be considered an approximation.

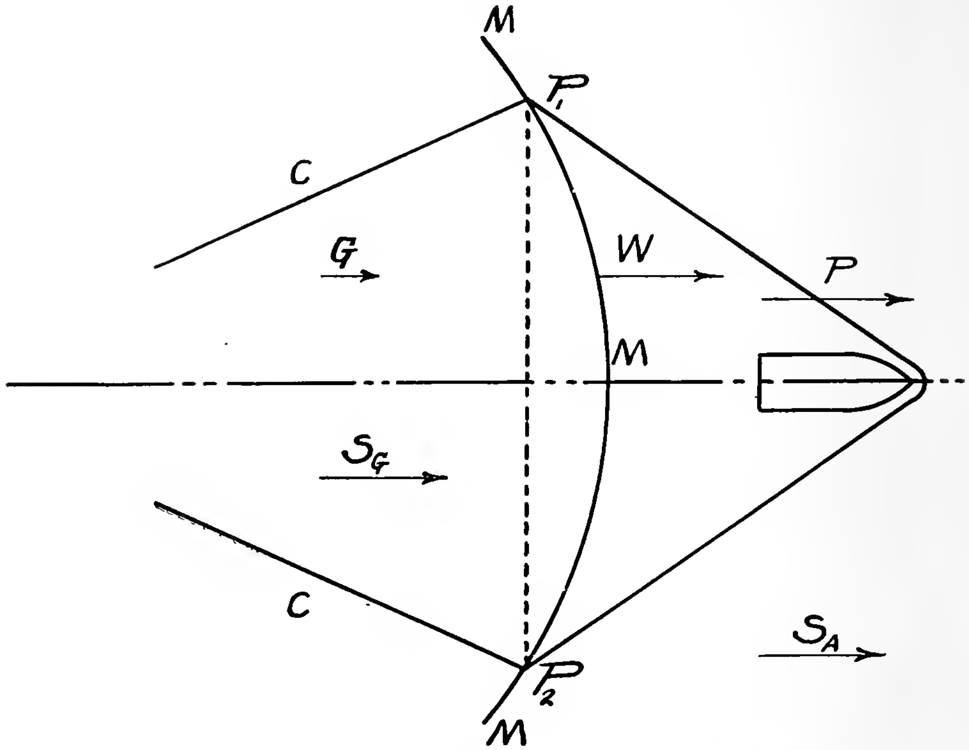

FIG. 28.—*Diagrammatic presentation of gas and wave speeds as deduced from Figure 27*

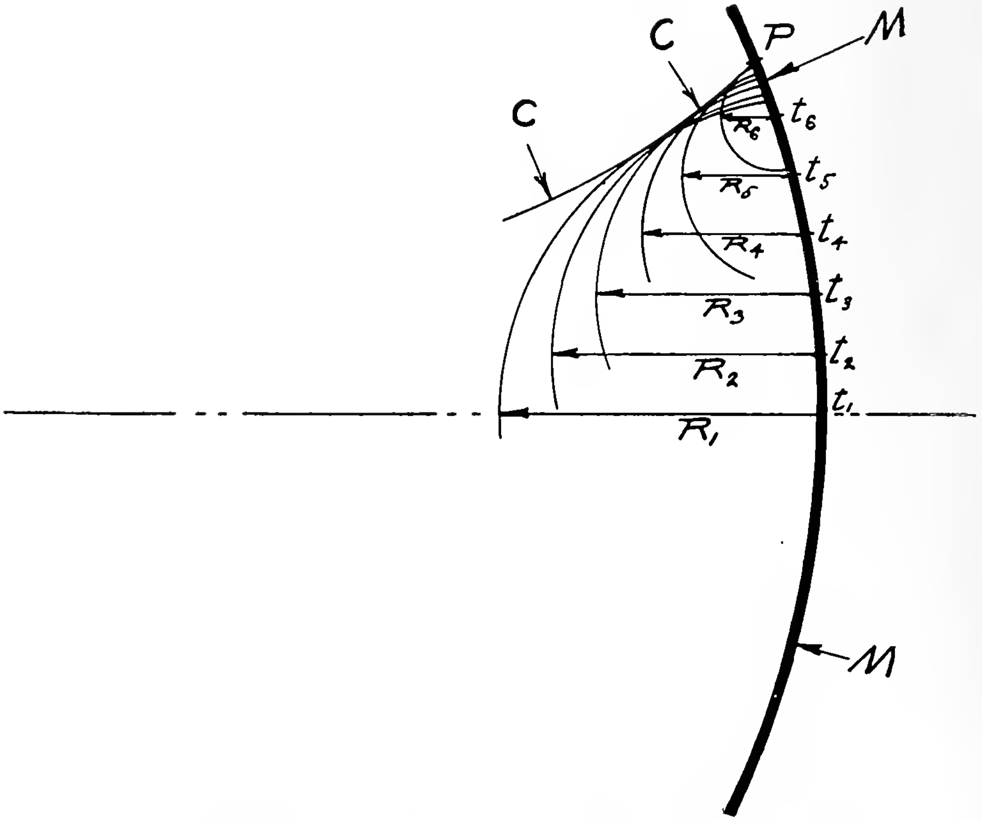

FIG. 29.—*Illustrating the origin of the trailing wave CC in Figure 16*

Referring to Figure 29, a uniform time scale is laid off along M, and from each of these points circles are drawn whose radii increase by equal amounts as we proceed backward from the actual position of the singular point P. The envelope of all such waves will be the wave CC, which, since the source P is moving along a curved path, will be slightly concave upward, as observed on the photographs.

Attention should be called to the varying character of the wake behind the projectile under varying circumstances. The speeds of all the rifle projectiles shown in the photographs were substantially the same, yet there is considerable variety in the character of the wakes. In Figures 7, 8, and 9 the wake is constricted near the base. In Figure 35, which shows the tracer bullet, this constriction is absent and the base wave is exceptionally faint. In Figures 16 and 27, where the projectile has just emerged from the discharge gases there is again no constriction; in fact, the wake broadens out. Again, in Figure 31, where the projectile has just emerged from a soap bubble containing gas in which the speed of sound is greater than that of the projectile, the wake is constricted less than in Figure 33, where the speed of sound in the gas is less. These wake characteristics, when understood, will undoubtedly throw light on the motion of the gas in the immediate vicinity of the projectile. There has not been time to follow out this interesting phase of the problem and to make additional experiments designed to obtain information leading to a satisfactory explanation.

The apparent straightening out of the wave M in the region between the head and base waves of the projectile is not real, but due to distortion in projecting upon the plate the intersection of the conical sound wave from the projectile with the wave M from the muzzle. In analyzing spark photographs of the type here discussed the fact that the projection is not orthographic must always be kept in mind.

XIII. MODIFICATION OF SOUND WAVES BY THE MEDIUM A

The explanation by C. V. Boys of the formation of the sound waves which attend the motion of a projectile makes it clear that none can be formed unless the speed of the projectile is equal to or greater than the speed of sound in the medium. Since the speed of sound in hydrogen gas is considerably greater than that of the service projectiles it follows that a projectile entering a soap bubble filled with hydrogen gas should lose its head and base waves, which should redevelop as the projectile emerged into the air.

In Figure 30 is shown a modified .30-caliber service bullet just after entering such a soap bubble filled with a mixture of hydrogen and air. The amount of hydrogen present in the gas inside the

bubble was sufficient to raise the speed of sound above the speed of the projectile, as is indicated by the absence of head and base waves while the projectile is inside of the bubble. It will be seen that the bullet did not enter the bubble quite centrally, but was displaced sideways as well as being a little low. Just ahead of the nose of the projectile is seen a sound wave which was started by the projectile

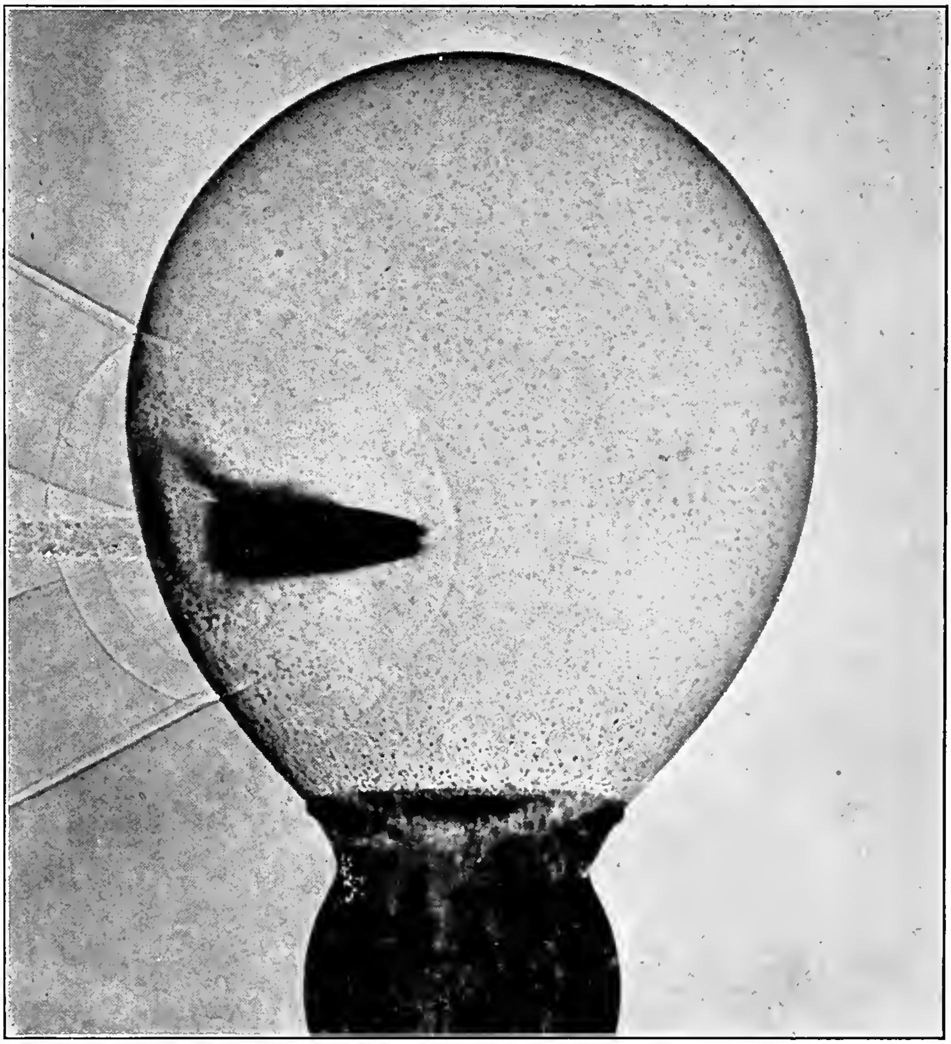

Fig. 30.—*.30-caliber service bullet with modified head entering a soap bubble filled with a mixture of hydrogen and air*

There was sufficient hydrogen present to raise the speed of sound inside the bubble above that of the bullet and hence no head wave could be formed. The wave just ahead of the nose of bullet was started when the bullet struck the side of the bubble. It is moving faster than the bullet. This bullet entered the bubble eccentrically, to one side and a little low.

in striking the side of the bubble and which is traveling somewhat faster than the projectile itself. By measuring the relative distance each has traveled it may be shown that the speed of this wave is approximately 3,200 ft./sec.

The apparent extension of the head waves and their reflected portion into the interior of the bubble is a perspective effect due to

the fact that the projectile is not moving in a plane passing through the center of the bubble and parallel to the plane of the paper.

Figure 31 shows the same type of .30-caliber projectile after passing through a similar bubble filled with a mixture of hydrogen and air. In this photograph the sound waves attending the projectile have been considerably modified, and it is interesting to see how this has come about.

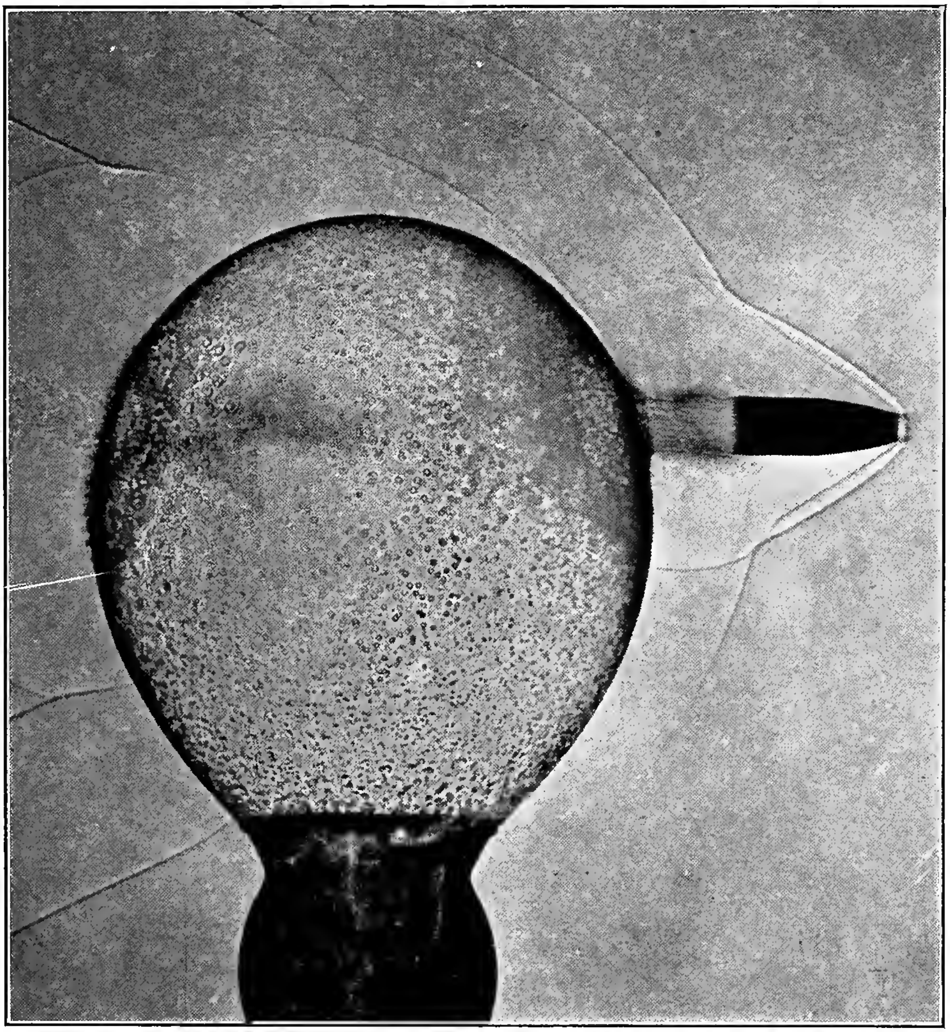

FIG. 31.—*.30-caliber service bullet with modified head after passing through a soap bubble filled with a mixture of hydrogen and air*

Note modification of the head and base waves.

Referring to Figure 32, consider a bullet whose point is at the position P_1. If this projectile were moving at a speed of 2,700 ft./sec. in air, it would generate a sound wave which would lie approximately along the line P_1P_3. If, on the other hand, the bullet were moving in an atmosphere in which the speed of sound was n times that in air, but still less than the speed of the bullet, the wave front generated by

the bullet would lie along the line P_1P_2. Let the line XYP_1 represent the bounding surface of the gas in which the speed of sound is n times that in free air.

We shall now proceed to find the form of the sound wave in air, represented in the diagram by the line $P_3\,DEFP_1$ after a portion of it has passed through the gas inside the surface XYP_1, in which we have postulated that the speed of sound is n times that in air.

Consider the point a_3 at which the wave front would have arrived if in the higher speed gas only. In the actual case the wave has traveled toward the position a_3 along the path a_2a_3 in air instead of gas and, therefore, this distance must be divided by n. Proceeding in

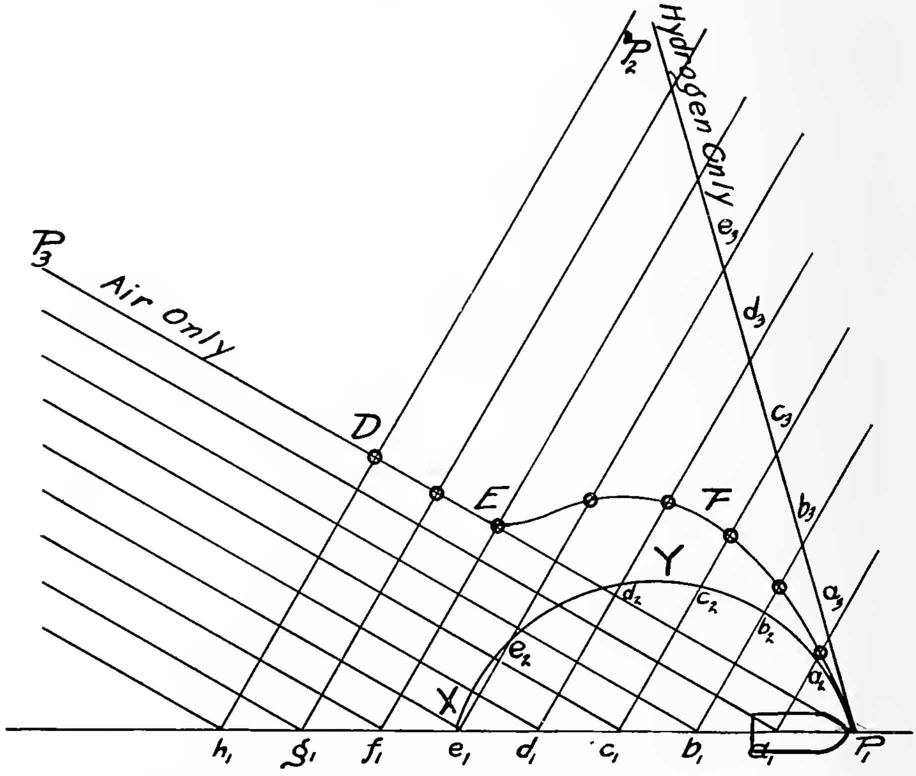

Fig. 32.—*Geometrical analysis of sound-wave modification in and around a soap bubble filled with a gas other than air*

this way we get the points of the curve $DEFP_1$ which represents the modified surface of the original P_1P_3. The configurations of the sound waves in Figures 31, 33, and 34 show this general character and are explainable in this way.

Figure 33 shows an ordinary pointed .30-caliber projectile at about the same stage as the modified one in Figure 31.

The bubble of this photograph (fig. 34) contains enough hydrogen to raise the speed of sound in the gas in its interior above that of the bullet, hence no waves of the usual character were generated in this space. That is to say, abrupt discontinuities in the sound waves occurred at each side of the bubble.

1. TRACER BULLETS

It appears to have been generally believed that the strong light which tracer bullets emit would make it impossible to photograph them successfully, and visual observation tended to confirm this belief. Figure 35, however, is a photograph of a tracer bullet taken approximately 35 feet from the muzzle. This photograph was obtained by using a rectangular tube of black paper with its axis transverse to the trajectory and coincident with the line joining the spark gap and the center of the photographic plate. By this device the plate was shielded against the tracer light before and after the

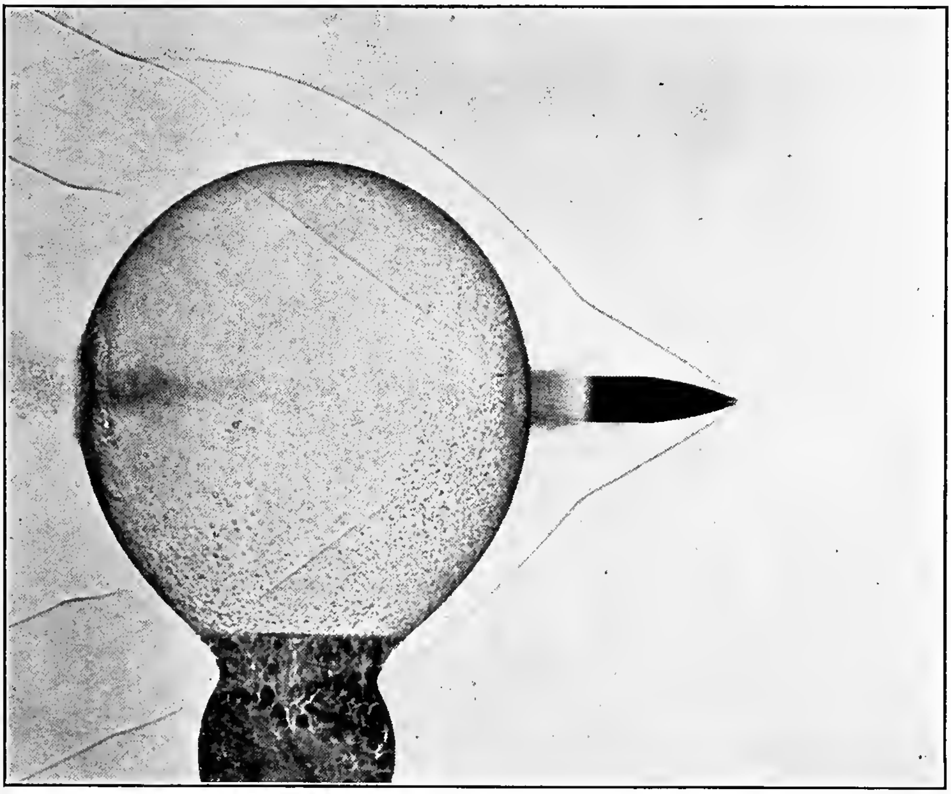

FIG. 33.—*.30-caliber service bullet after passing through a soap bubble filled with a mixture of hydrogen and air*

Note modification of head and base waves.

bullet had traversed the tube. The plate is fogged, of course, but it nevertheless shows some interesting details.

The most striking thing is the almost complete absence of a base wave. (See fig. 7.) The usual base wave is undoubtedly associated with the rapid pressure change at the base which accompanies the partial vacuum behind it. Apparently the gases generated by the tracing compound prevent the formation of a region of diminished pressure, and hence the formation of a base wave.

About 2 inches back from the base of the tracer bullet particles of the tracing compound can be seen as they leave the wake.

2. COMPRESSED AIR CAP ON NOSE OF PROJECTILE

A white axial line which apparently splits the nose of the projectile is found in all photographs which have been made with the new apparatus. Exhaustive experiments indicated that this is not due to any characteristics of the spark, and to get further information on this point a portion of the nose was machined off several projectiles, so as to give various degrees of bluntness. The photographs of these modified projectiles indicate that the line which apparently splits the nose of the projectile is really the apex of a very sharp wedge of light

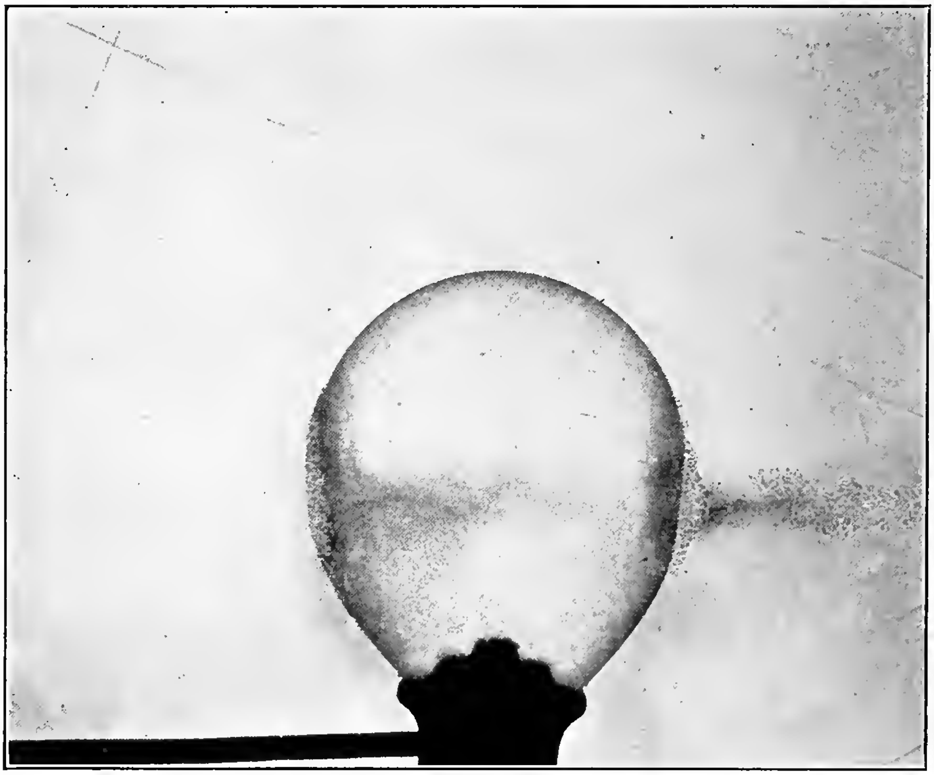

FIG. 34.—*Head and base waves of a .30-caliber service bullet*

There was sufficient hydrogen in this bubble to raise the speed of sound inside the bubble above that of the bullet, hence the head and base waves ceased as the bullet entered the bubble and began again as it emerged. The reflections of the head and base waves are to be noted above and to the rear of the bubble. The change in cross section of the wake at the point of emergence from the bubble is also significant. It is to be expected that in its progress through hydrogen the bullet will carry more of the medium with it than in air. The photograph affords visual evidence of this.

which is bent around the nose of bullet presumably by the head wave and falls upon the plate inside the shadow of the projectile. These details while clearly shown on the negatives are either very faint or entirely lost on the reproductions. The shape of this wedge varies with the curvature of the head wave, which, in turn, changes with the degree of bluntness of the projectile as indicated in Figure 36.

The mass of compressed air which a projectile pushes ahead of its nose undoubedly contributes to the modification of the effect observed on the more pointed types of projectiles.

In conclusion, the author wishes to express his indebtedness to Dr. E. A. Eckhardt for suggestions and assistance in the experiments and in the preparation of the manuscript and to Drs. L. J. Briggs and

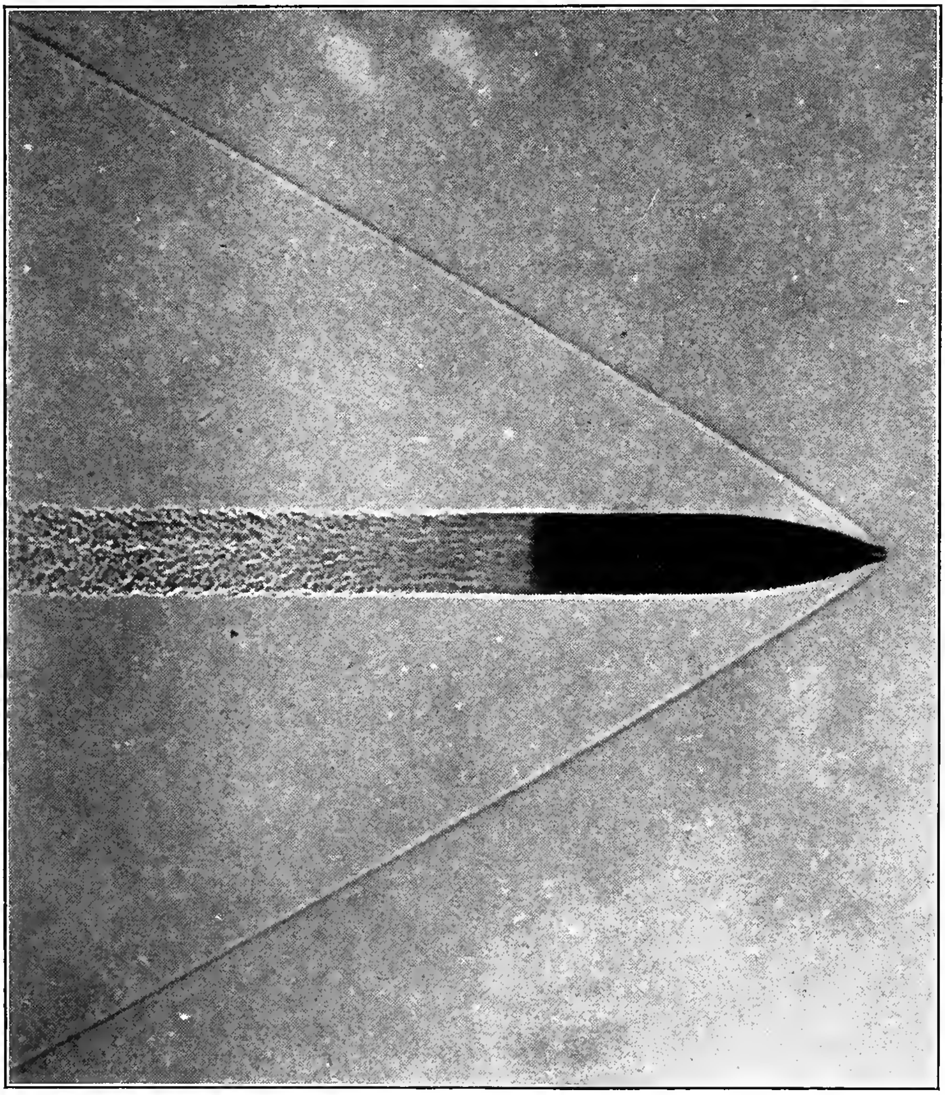

FIG. 35.—*.30-caliber tracer bullet taken approximately 35 feet from the muzzle*
Note the almost complete absence of the base wave.

E. Buckingham for their kindly interest in the experiments and their helpful suggestions and criticisms.

The courtesy of the Frankford Arsenal in furnishing some of the arms and ammunition is gladly acknowledged. Most of the photographs here presented were taken in the process of developing the design of bullet-photography apparatus for the use of that organization.

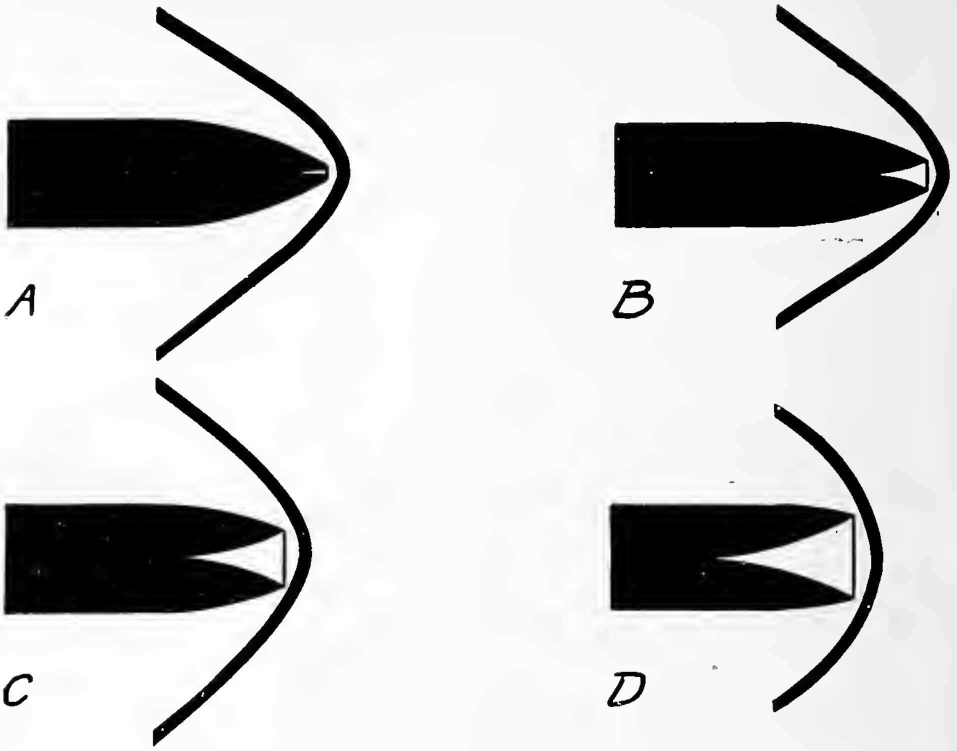

FIG. 36.—*Illustrating the progressive stages of development of the wedge shaped figure which occurs at the point of the projectile*

"*A*" normal .30-caliber service bullet, "*B*," "*C*," and "*D*" modified forms of the service bullet. Scale twice actual size.

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